HEAT AND MASS TRANSFER DURING COOKING OF CHICKPEA – MEASUREMENTS AND COMPUTATIONAL SIMULATION

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ABSTRACT

Chickpea is a food legume crop grown in tropical, sub-tropical and temperate regions. World chickpea production is roughly three times that of lentils. Among pulse crops marketed as human food, world chickpea consumption is second only to dry beans. Turkey, Australia, Syria, Mexico, Argentina and Canada are major chickpea exporters.

There are two types of chickpea, namely, the kabuli and the desi. The kabuli type is grown in temperate regions while the desi type chickpea is grown in the semi-arid tropics. Chickpea is valued for its nutritive seeds with high protein and starch content. They are eaten fresh as green vegetables, parched, fried, roasted, and boiled, as snack food, dessert and condiments. The seeds are ground and the flour can be used in soup, dhal and bread. Cooked chickpea is mostly preferred by consumers, especially the kabuli type.

In this thesis, the heat and moisture transfer behavior of kabuli chickpea when subjected to cooking at different temperatures was investigated. The thermo-physical properties of chickpea were studied to develop a model to simulate the temperature distribution and moisture absorption in a chickpea seed when cooked in water.

The thermo-physical properties determined experimentally were thermal conductivity, specific heat, moisture diffusivity, particle density and moisture content. Thermal diffusivity was calculated using the experimental values of thermal conductivity, specific heat and density. The water absorption in chickpea was determined when the seeds were soaked at different temperatures. It was observed that as the temperature of the soaking medium was increased, the rate of moisture absorption also increased. Soaking was done to enhance the gelatinization process during cooking. Cooking experiments were conducted for boiling temperatures ranging from 70 to 98°C for both soaked and unsoaked seeds. It resulted in the soaked seeds being cooked within 40-50 min, whereas the unsoaked seeds took around 250-300 min to cook. The amount of soluble solids lost during the cooking process is also reported which enables to predict the optimum soaking and cooking temperature.

Using linear regression simple models for dependency of thermal conductivity, specific heat, thermal diffusivity and density on temperature and moisture content were developed. The rate of moisture transfer and the center temperature in the seed during cooking was determined experimentally and also simulated with the constant thermal properties found experimentally. The closeness of the simulated and experimental results was proved by appropriate statistical analysis.

Based on the results obtained, it can be understood that soaking the chickpea seeds at temperatures ranging from 25 to 40°C for 8 h and cooking it at higher temperatures ranging from 90 to 100°C will improve the quality of the cooked seed with minimum mass loss. This optimum condition saves both energy and time.

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DEDICATION

I dedicate this thesis to my beloved family.

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1. INTRODUCTION

Food legumes have been well recognized as valuable source of dietary proteins in many parts of the world. A major portion of the world population relies on legumes as staple food particularly in combination with cereals.

Chickpea (*Cicer arietinum* L.) is a cool season food legume crop grown in more than 45 countries of the world. It is the third most commonly consumed legume in the world (Singh et al., 1991). It is one of the staple foods in the Middle Eastern countries, and half of the world's annual chickpea production comes from Syria and Turkey (Singh et al., 1990).

Chickpea is commonly utilized in whole or paste form as a main or side dish after cooking (Amr and Yaseen, 1994) and in whole form as a snack food after roasting (Koksel et al., 1998). Different heat treatment methods are used to prepare chickpea namely, conventional methods like cooking in water, pressure cooking, roasting, puffing and modern methods like microwave and infrared heating. Chickpea cooked in water is mostly preferred by consumers since it produces a tender edible product with aroma. Cooking also inactivates antinutritional factors present in the grain. There are two main types of chickpea namely, the kabuli and the desi, but the most preferred type for cooking is the kabuli. Kabuli seeds are large in size, salmon white in color and contain high levels of carbohydrates and proteins.

Legume grains require a relatively long cooking time ranging from 1 to 4 h (FAO, 1979). Each cooking process involves simultaneous heat and mass transport phenomena, physical and chemical reactions such as starch gelatinization and protein denaturation.

Boiling is performed at temperatures below or around 100˚C in either water or soups (Skjoldebrand, 1984). Absorption of water by the chickpea during soaking and boiling at relatively low temperatures below 100˚C promotes a soft and moist product texture, with minimal mass loss. Cooking time of legumes primarily depends on the softness of the cooked seeds. In order to find the optimum cooking time, information on the thermal properties and the heat and mass transfer characteristics should be known.

Previous studies were done on different methods of cooking chickpea based on its cooking time and nutritional factors. However, heat and mass transfer characteristics of chickpea has so far not been studied. The relationship between cooking time and some physical characteristics in chickpea was studied by Williams and co-workers (1983), however, not much work was done on the thermal properties of chickpea. Traditionally prior to cooking, chickpea grains should be soaked for a period of approximately 10 to 12 h. The size, composition and structure of legume seed, water absorption and rate of heat transfer, has a large influence on the cooking time and quality of the cooked seed. Therefore, any preliminary processing that causes changes in the characteristics of the seed affects the cooking properties. In order to maintain the appearance, texture, structure of the seed and prevent them from splitting and damaging the seed when subjected to cooking in water, suitable models for heat and moisture transfer of the seed should be developed. Based on the results obtained, optimum soaking and cooking time can be determined. In this study, emphasis has been given on the thermo-physical properties and the heat and mass transfer characteristics during cooking.

Mathematical modeling and simulation of the cooking process play an important role in designing and optimizing the cooking process. The current research involves modeling, simulating and validating the heat and moisture transfer phenomena within the chickpea seed during cooking process to predict the heat and the moisture transfer within the seed. Mathematical equations were developed of the time-dependent heat and moisture transfer into the seed.

The objectives of this thesis are given in chapter 2 and the literature review is presented in chapter 3. The materials and methods are explained in chapter 4. Chapter 4 has a detailed description on the experiments that were conducted. Mathematical modeling and simulation information are presented in chapter 5. In chapters 6 and 7, the results are analyzed and discussed and the summary and conclusions is presented. Recommendations are given in chapter 8. Results of the simulation on temperature distribution and moisture diffusion are given in the appendices.

2. OBJECTIVES

The principal objective of this thesis is to model and simulate heat and mass transfer during cooking of chickpea seed with water and to predict the optimum cooking time. The specific objectives are:

1) to develop heat and mass transfer equations during cooking of chickpea grain ;
2) to study the thermo-physical properties of the chickpea grain ;
3) to experimentally measure the temperature distribution and moisture absorption of the grain during cooking ; and
4) to predict the temperature distribution and moisture absorption during cooking of chickpea grain and validate the model predicted results with the experimental data.

3. LITERATURE REVIEW

This chapter consists of two sections. The first section is a review of the thermo-physical properties, soaking and water absorption, and the cooking characteristics of the chickpea grain. The second section is a review of the heat and mass transfer theories and the relevant numerical techniques to solve the equation systems. Application of the heat and mass transfer model in the food system is also reviewed in the second section.

3.1 Thermo-physical Properties

In order to conduct effective process modeling and simulation in each application at every stage, there is a need for consistent thermo-physical property information. Hence a review of thermo-physical properties that have been reported in literature is addressed in this section.

3.1.1 Physical properties

Some of the physical properties include 1000-grain weight, sphericity, roundness, size, volume, shape, surface area, bulk density, kernel density, porosity, static coefficient of friction against different materials and angle of repose. Limited research has been conducted on the physical properties of chickpea. Some engineering properties of chickpea seeds, such as density, terminal velocity and coefficient of drag, were reported by Kural and Carman (1997).

Sphericity is defined as the ratio of the surface area of a sphere, which has the same volume as that of the solid, to the surface area of the solid. Roundness of a solid is a measure of the sharpness of its corners and is defined as the ratio of the largest projected area of an object in its natural rest position to the area of the smallest circumscribing circle (Curray, 1951). Cadle (1995) described various methods of determining a characteristic dimension of irregular shaped solids. Several methods of determining the sphericity and roundness have been listed by Mohsenin (1970) and according to him, the method suggested by Curray (1951) is subjected to the least criticism. The size distribution of chickpea (*Cicer arietinum* L.) is shown in Table 3.1.

Table 3.1 Sphericity and roundness of chickpea at three mutually perpendicular positions* (standard deviation in parenthesis) (Dutta et al., 1988a).

Rest position	With root		Root ignored	
	Sphericity	Roundness	Sphericity	Roundness
1	0.703	0.640	0.818	0.829
	(0.026)	(0.023)	(0.034)	(0.033)
2	0.691	0.637	0.802	0.796
	(0.033)	(0.031)	(0.037)	(0.041)
3	0.810	0.814	0.810	0.814
	(0.021)	(0.027)	(0.021)	(0.027)
Mean	0.735	0.697	0.810	0.813
Standard deviation	0.053	0.082	0.006	0.013

* Number of replications =20

Henderson and Pabis (1962) used the geometric average of three principal dimensions for the diameter of an equivalent sphere. Later Pabis (1967) defined effective diameter in terms of 1000-grain weight and kernel density as:

$$d_e = \left(\frac{6W_{1000}}{1000\rho_b \pi} \right)^{\frac{1}{3}} \tag{3.1}$$

where:

d_e = effective diameter (m) and

ρ_b = bulk density of the grain (kg/m^3).

The geometric mean diameter d_p of the seed can be calculated by using the following relationship (Mohsenin, 1970):

$$d_p = (LWT)^{\frac{1}{3}} \tag{3.2}$$

where:

L = length (mm),

W = width (mm) and

T = thickness (mm).

Table 3.2 shows the dimensions of the seed at 5.2% moisture content reported by Konak et al. (2002), where about 70% of the seeds have a length ranging from 8.50 to 9.50 mm and about 85 to 89% width and thickness ranging from 7.00 to 8.00 mm.

Table 3.2 Physical attributes of chickpea seed at 5.2% dry basis (Konak et al., 2002).

Attribute	Mean ± SD
Length, mm	9.342 ± 0.118
Thickness, mm	7.752 ± 0.087
Width, mm	7.722 ± 0.103
Geometric mean diameter, mm	8.358 ± 0.089
Sphericity, %	87.589 ± 0.474
Mass, g	0.324 ± 0.003
Volume, cm^3	0.238 ± 0.027

SD = Standard deviation

Bulk density is the ratio of the mass of a sample of food grain to its total volume. It is a moisture dependent property and is found by filling a standard container with grain by pouring it from a certain height, striking off the top level and then weighing the contents. Bulk density of the seeds varied according to different moisture levels from 741.4 to 800 kg/m^3 and indicated a decrease in bulk density with an increase in moisture content (Konak et al., 2002). The inverse linear relationship of bulk density with moisture content was also reported for pigeon pea (Shepherd and Bhardwaj, 1986) and soybean (Deshpande et al., 1993).

The kernel density of a seed is defined as the ratio of the mass of a sample of a seed to the solid volume occupied by the sample (Deshpande et al., 1993). Kernel density of chickpea at different moisture levels varied from 1428 to 1368 kg/m^3. As moisture content increased, the kernel density of chickpea seed decreased (Konak et al., 2002).

Porosity is the property of the grain, which depends on its bulk and kernel densities. The values of porosity of various grains as measured with the help of an air comparison pycnometer which measures the volume by using high pressure air was reported by Thompson and Isaacs (1967). The air comparison pyconometer displaces high pressure air which is measured with the help of a manometer and the displaced volume is measured. The porosity, ε of bulk seed is computed from the values of kernel density in the relationship given by Mohsenin (1970) using the following equation:

$$\varepsilon = \frac{\rho_k - \rho_b}{\rho_k} 100 \tag{3.3}$$

where:

ρ_b = bulk density (kg/m^3), and

ρ_k = kernel density (kg/m^3).

Porosity of chickpea seed increases with an increase in moisture content from 5.2 to 16.5% d.b. (Konak et al., 2002). Carman (1996) reported a similar increase in porosity from a moisture content of 27.5 to 32.2% (d.b.) for lentil.

Projected area of chickpea seed increased by about 22.4%, when the moisture content of seed increased from 5.2 to 16.5% d.b. Similar trends were observed in other seeds (Mohsenin, 1970; Sitkei, 1986).

The angle of repose of the chickpea seed increased from 24.5 to 27.9ºC in the moisture range of 5.2-16.5% d.b. The value of angle of repose for chickpea seed was considerably less than those reported for pumpkin, pigeon pea and fababean seeds (Fraser et al., 1978; Shepherd and Bhardwaj 1986). This may be due to the higher sphericity of chickpea seeds allowing them to slide and roll on each other (Konak et al., 2002).

Rupture strength is usually dependent on the moisture content. The highest rupture force obtained was 210 N at a moisture content of 5.2% d.b (Konak et al., 2002). Generally the seeds became more sensitive to cracking at high moisture content; hence, they required less force to rupture.

3.1.2 Thermal properties

Thermal properties include specific heat, thermal conductivity and thermal diffusivity. Specific heat is the quantity of the heat that is gained or lost by a unit mass of product to accomplish a unit change in temperature, without a change in state. It can be calculated as follows:

$$c_p = \frac{Q}{m(\Delta T)} \tag{3.4}$$

where:

Q = heat gained or lost (kJ),

m = mass (kg),

ΔT = temperature change in the material (K), and

c_p = specific heat (kJ/ kgK).

Specific heat is an essential part of the thermal analysis of food processing or of the equipment used in heating or cooling of foods. A number of models express specific heat as a function of water content, as water is a major component of many foods. Siebel (1892) proposed that the specific heat of food materials such as eggs, meats, fruits and vegetables can be taken as equal to the sum of the specific heat of water and solid matter. One of the earliest models to calculate specific heat was proposed by Siebel (1892) as:

$$c_p = 0.837 + 3.349\,X_w \tag{3.5}$$

where:

X_w = water content expressed as a fraction.

The influence of product components was expressed in an empirical equation proposed by Charm (1978) as:

$$c_p = 2.093\,X_f + 1.256\,X_s + 4.187\,X_w \tag{3.6}$$

where:

X = mass fraction, and

subscripts:

f = fat, s = nonfat solids, and w = water.

Other equations of similar form as Equation 3.5 have been summarized by Sweat (1986). Choi and Okos (1983) gave a more generalized equation for specific heat which takes into account the composition of food:

$$c_p = 4.180\,X_w + 1.711\,X_p + 1.928\,X_f + 1.547\,X_c + 0.908\,X_a \tag{3.7}$$

where:

X = mass or weight fraction of each component.

The subscripts denote the following components:

w = water, p = protein, f = fat, c = carbohydrate and, a = ash.

Although specific heat varies with temperature, for ranges near room temperature, these changes are relatively minor. They are usually neglected in engineering calculations. Sweat (1986) gave several equations for specific heat which include temperature dependency.

Specific heat measurements can be done by the method of mixture, comparison method, adiabatic method and differential scanning calorimetry (DSC). However in the case of food materials, there are some problems due to direct mixing. The density of the heat transfer medium should be lower than the food sample so that it will sink more readily. Hwang and Hayakawa (1979) developed a calorimeter for measuring specific heat of food materials by avoiding direct contact between food and heat exchange medium in the calorimeter. The DSC is well-suited for determining the effect of temperature on specific heat of food samples because it is easy to scan a wide range of temperatures (Rao and Rizvi, 1995). The dynamic feature of DSC allows the determination of specific heat as a function of temperature (Tang et al., 1991). McMillin (1969) and Koch (1969) employed DSC to determine the specific heat of wood and dry tree bark, respectively. Using DSC, Murata et al. (1987) determined the specific heat of eight cereal grains over a temperature range of 10 to 70°C and a moisture content range of 0 to 35% w.b. Tang et al. (1991) determined the specific heat capacity of lentil seeds by DSC and reported that specific heat increased quadratically with moisture content over the range from 2.1 to 25.8% w.b. and linearly with temperature varying from 10 to 80°C. The use of DSC for measuring the heat capacity of chickpea was not reported.

The thermal conductivity of a food material is an important property used in calculations involving rate of heat transfer. In quantitative terms, this property gives the amount of heat that will be conducted per unit time through a unit thickness of the material, if a unit temperature gradient exists across that thickness. Hooper and Lepper (1950) determined thermal conductivity using the following equation:

$$k = \frac{Q}{4\pi\Delta T}\ln\left(\frac{t_2}{t_1}\right) \tag{3.8}$$

where:

k = thermal conductivity (W/mºC),

Q = heat input (W),

T = temperature (ºC),

$\Delta T = T_2 - T_1$, and

t = time (s).

Most high moisture foods have thermal conductivity values close to that of water. On the other hand, the thermal conductivity of dried, porous foods is influenced by the presence of air with its low thermal conductivity value. Empirical equations are useful in process calculations where the temperature may be changing. For fruits and vegetables with water content greater than 60%, the following equation has been proposed (Sweat and Haugh, 1974):

$$k = 0.148 + 0.493X_w \tag{3.9}$$

where:

k = thermal conductivity (W/mºC),

X_w is the water content expressed as mass fraction.

Another empirical equation developed by Sweat (1986) is for solid and liquid foods:

$$k = 0.25X_c + 0.155X_p + 0.16X_f + 0.135X_a + 0.58X_w \qquad (3.10)$$

where:

X = mass fraction,

subscripts:

c, p, f, a and w = carbohydrate, protein, fat, ash, and water, respectively.

Thermal diffusivity, a ratio involving thermal conductivity, density and specific heat is given as:

$$\alpha = \frac{k}{\rho c_p} \qquad (3.11)$$

where:

α = thermal diffusivity (m^2/s),

ρ = density (kg/m^3),

k = thermal conductivity (W/mºC), and

c_p = specific heat (kJ/kgºC).

Literature reveals that there is not much data on thermal properties of chickpea (*Cicer arietinum* L.*)* (Dutta et al., 1988b). The bulk thermal conductivity of grains is determined in different ways. The one-dimensional steady-state heat flow method has been reported to have a disadvantage because a long time is required to attain the steady-state and there is a possible migration of moisture due to temperature differences maintained across the grain for long periods of time. These difficulties can be avoided by using the transient heat flow method for finding the thermal conductivity of different grains (Shepherd and Bhardwaj, 1986). Kazarian and Hall (1965) and Shepherd and Bhardwaj (1986) found thermal diffusivity from the measured values of specific heat, bulk thermal conductivity and bulk density; the former have established that the calculated values of diffusivity thus obtained, were 6.1 to 11.6% greater than the measured value for wheat at various moisture levels, using the transient heat flow method. The specific heat of chickpea, at five moisture levels of 12.4, 16.6, 20.5, 24.6 and 32.4% in four temperature ranges was reported to be between 1464 and 2904 J/kgK (Dutta et al., 1988b). The specific heat was found to increase both with increase in moisture content and temperature (Dutta et al., 1988b). The thermal conductivity of chickpea, obtained experimentally in the moisture ranges of 11.5 to 27.2% and 283 to 312 K respectively, was found to be between 0.114 and 0.247 W/mK (Dutta et al., 1988b). It is observed that the thermal conductivity increases both with temperature and moisture content. The thermal conductivity of chickpea is observed to be higher than that of pigeon pea, sorghum and wheat, but lower than that of bean and corn (Shepherd and Bhardwaj, 1986). Thermal diffusivity of chickpea ranged from 9.46×10^{-8} to 16.39×10^{-8} m^2/s in the moisture and temperature ranges of 12.5 to 26.5% (d.b.) and 293 to 307 K, respectively (Dutta et al., 1988b).

3.1.3 Soaking and water absorption

Understanding water absorption in legumes during soaking is of practical importance since it affects subsequent processing operations and the quality of the final product. Hence, modeling moisture transfer in grains during soaking has attracted considerable attention. Many theoretical and empirical approaches have been employed and in some cases empirical models preferred because of their relative ease of use (Nussinovitch and Peleg, 1990; Singh and Kulshrestra, 1987).

Seeds are usually soaked before dehulling and cooking. Soaking is the first step during processing of chickpea, and other edible seeds and grains. The principal reason for soaking is to hasten the gelatinization of starch in the seed. It can be achieved either through conditioning below the gelatinization temperature and then cooking above the gelatinization temperature, or through direct cooking above the gelatinization temperature.

Peleg (1988) proposed a two-parameter sorption equation and tested its prediction accuracy during water vapor adsorption of milk powder and whole rice, and soaking of whole rice. This equation has since been known as the Peleg model (Equation 3.12). The Peleg model is acceptable for predicting moisture content of different types of chickpea during soaking.

$$M = M_0 \pm \frac{t}{K_1 + K_2 t} \tag{3.12}$$

where:

M = moisture content at time t (% d.b),

M_0 = initial moisture content (% d.b),

K_1 = Peleg rate constant ($h\%^{-1}$),

K_2 = Peleg capacity constant ($\%^{-1}$), and

t = time (h).

Here the equation is '+' since the process is absorption. Sayar et al. (2001) analyzed chickpea soaking in water within a wide temperature range through a theoretical approach considering the phenomena as a simultaneous water transfer and water-starch reaction. Turhan et al. (2002) studied the suitability of the Peleg model for describing water absorption of chickpea during soaking over a wide temperature range covering the conditioning and cooking temperatures. They reported that the Peleg rate constant K_1

increased with temperature linearly or nonlinearly depending on the product and could be useful in estimating approximate gelatinization temperature of starchy grains utilizing the Arrhenius plot. They also proved that the Peleg capacity constant K_2 may increase or decrease with increasing temperature depending on the sample and the method of moisture content calculation used. Menkov (2000) studied the moisture sorption isotherms of chickpea seeds at several temperatures and reported that the sorption capacity of chickpea seeds decreased with an increase in temperature at constant water activity. Klamczynska et al. (2001) reported that after 8 hours of soaking, the weight increase of chickpea reached a plateau, resulting in a 40% increase in seed mass. It is essential to understand the water absorption characteristics at different temperatures, since this work involves heat and mass transfer. Generally, water absorption in desi and kabuli chickpea increased significantly during 16 h of soaking period, but maximum rapid water absorption was recorded during the first 4 h and thereafter, the rate slowed down. Water absorption values decreased in kabuli chickpea, but increased in desi chickpea during storage (Gulati et al., 1997). Water absorbing capacity depends upon the cell wall structure, composition of seed and compactness of the cells in seeds (Muller, 1967).

3.1.4 Cooking characteristics of chickpea

Cooking is done in water above the gelatinization temperature so that starch granules gelatinize, thus converting the chickpea into an edible and processable form (Sayar et al., 2001). Cooking time in both desi and kabuli chickpeas increased during storage but all kabuli types exhibited higher cooking time in fresh samples than in stored samples. The effect of physicochemical properties of chickpea due to different cooking methods is discussed in the following paragraphs. The different types of heat treatment methods like conventional methods and modern methods of cooking are also mentioned.

3.1.4.1 Effect of cooking on chickpeas

The protein content of chickpea seeds is highly variable and determined by both genetic and environmental factors. Chickpea seed contains 14.5 to 30.6% crude protein (Chavan et al., 1986). The chemical composition and nutritive value of chickpea proteins are both affected by processing methods (Singh, 1985). Chickpea seed is processed and cooked in a variety of forms depending upon traditional practices and taste preferences (Clemente et al., 1998). Different methods (decortication, soaking, sprouting, fermentation, boiling, roasting, parching, frying, steaming) remove anti-nutritional factors and increase the protein digestibility of chickpea seeds (Attia et al., 1994). Increasing the time and temperature of cooking was reported to reduce the availability of lysine in chickpea seed (Rama Rao, 1974). To minimize amino acid losses, cooking of chickpea in an autoclave (121ºC) for 1 h has been suggested (Youseff, 1983). It was reported that shorter cooking time resulted with softer seed, and lower force needed to deform the seed (Flinn et al., 1998). In order to prevent the development of hard-to-cook tendency in chickpea seeds, several pre-treatments like steaming, roasting, irradiation, solar drying and microwave application have been proposed for safe storage. Storage of chickpea seeds at high temperature and high relative humidity have been reported to cause detrimental changes in nutritional, physicochemical and functional characteristics (Reyes-Moreno et al., 2001). The data relating to the physicochemical characteristics of treated chickpea varieties HPG-17 and C-235 are given in Table 3.3. The 100-seed weight of the two varieties was 22.80 and 11.31 g, respectively. The 100 seed weight of the untreated as well as the treated seeds varied significantly. The highest 100-seed weight (51.07 and 25.07 g) was recorded for pressure-cooked seeds of both varieties. Waldia et al. (1996) reported that the 100-seed weight of chickpea cultivars ranged from 16.40 to 42.22 g.

Table 3.3 Physicochemical characteristics of heat treated chickpea (Sood and Malhotra, 2001).

Variety	Treatment	100-seed dry weight (g)	Density (gml^{-1})
HPG-17	Raw	22.80	2.42
	Soaked	44.73	2.15
	Pressure cooked	51.07	2.21
	Solar-cooked	49.20	2.18
	Parched	21.29	2.41
C-235	Raw	11.31	1.70
	Soaked	23.27	1.17
	Pressure cooked	25.07	1.28
	Solar-cooked	21.18	1.20
	Parched	10.11	1.48
CD ($P \leq 0.05$)		2.33	1.84
SE		0.81	0.06

CD = Critical difference; SE = Standard error

The density of chickpea varied significantly when the seeds were heat treated employing different method. The density of raw seeds was higher than that of seeds subjected to soaking, pressure cooking, solar cooking and parching (Sood and Malhotra, 2001).

The cotyledon cells of dry chickpea contain starch granules embedded in a protein matrix. The starch granules have different sizes with an oblong shape. There were similar irregular shapes of protein bodies nearly of a similar size. Soaking either in water or in $NaHCO_3$ led to a slight loss in some protein bodies due to the action of soaking solution in solubilizing the protein that stimulated the protease enzymes, and resulted in swelling and rupturing of these bodies. Precooking treatment carried out at temperature of more than 100°C, which was higher than the gelatinization temperature, led to the deformation of the swelled starch granules and the coagulation of protein. This deformation in the structure might be behind the softening of the chickpea. After drying, most of the protein coagulated and the starch granules disappeared. These results confirmed that most of the changes in the microstructure of chickpea were mainly due to heat treatment (El-Sahn and Youssef, 1992).

Hamza (1983) observed that high molecular weight proteins of raw chickpea changed to smaller sub units after soaking and heating processes. Cooking time in both desi and kabuli chickpeas increased during storage and all kabuli types exhibited longer cooking time in fresh as well as in stored samples (Gulati et al., 1997). Williams and co-workers (1983) viewed that cooking time in chickpea may be affected by the starch, the permeability of seed coat, internal structure and compactness of seed coat and endosperm material. They soaked the seeds in water and cooking time was recorded to be between 55 to 200 min. Punia and Chauhan (1993) recorded cooking time of 75 to 90 min in high yielding chickpeas and also reported that cooking time and water absorption of chickpea can be affected during storage. Klamczynska et al. (2001) investigated the distribution of protein, ash and starch in legume (chickpea, smooth and wrinkled peas) cotyledons, and the soaking and cooking characteristics including gelatinization and retrogradation of the starch.

Cenkowski and Sosulski (1998) determined the effects of micronization (high intensity infrared-heat) on water hydration rate and cooking time of split peas, and the functional properties of the protein and starch components. Dry peas can be instantized effectively by soaking at 99°C for 30 min and retort cooking at 110°C for 20 min (Bakker-Arkemma et al., 1969).

Reyes-Moreno et al. (2001) reported that chickpea developed the hard-to-cook (HTC) defect during storage at high temperatures (>25°C) and high relative humidities (RH >65%). The cooking time of whole grains of fresh chickpea varied from 112 to 142 min; these values were higher than those reported for other legumes such as common beans (59 to 90 min) (Reyes-Moreno and Paredes-Lopez, 1994). Adu and Otten (1996) studied the microwave heating and mass transfer characteristics of white bean seeds during drying and it was reported that drying rates progressively decreased with drying time and appeared to be independent of absorbed power during the latter stages of drying.

Wang et al. (1988) suggested that optimal cooking time occurs when the firmness of the cooked legumes reached appropriate values and to define the range of cooking acceptability, the degree of firmness of various commercially canned products was assessed using the back-extrusion test.

3.1.4.2 Conventional methods of cooking

Cooking in water: Legume seeds are commonly cooked in boiling water at extended periods of 1 to 4 h following overnight soaking. Cooking is generally done to produce a tender, edible product, to develop the aroma and to inactivate antinutritional factors present in the legume seeds. Cooking can be achieved at atmospheric or high pressure. Other cooking methods include roasting, extrusion cooking, and drum drying. Prolonged cooking results in destruction of amino acids, change in protein structure, and the reduction in the digestibility of proteins (Salunkhe et al., 1985).

Pressure cooking: Pressure cooking is common practice in many areas of the world for cooking whole seeds or dhal. Bressani (1993) reported that pressure cooking black beans for 10 to 30 min at 121ºC improved the utilization of black bean, as compared to raw beans. Bressani (1993) also reported that the *in vitro* digestibility of navy beans improved by mild heat treatment. Excessive heating reduced the nutritive value of the beans due to the destruction or inactivation of certain essential amino acids.

Roasting: This process involves the application of dry heat to legume seeds using a hot pan or dryer at a temperature of 150 to 200ºC for a short time, depending on the legume or the recipe to be made. Roasting produces a better product as far as protein quality is concerned than one produced by common wet cooking under pressure.

Puffing: Legumes may be puffed by subjecting them to high temperatures for a short time. At the home level, gentle heating to around 80ºC and then moistening with 2% water, which is absorbed overnight, may do this. The following day, the grain is roasted with hot sand at 250 to 300ºC at which point the cotyledons puff and split the husk, which is then removed by gentle abrasion. At the cottage industry level, puffing is accomplished with husk-fired furnaces and large toasting pans operated by a number of people. Fully automated, continuous oil-fired and electric roasting machines are also available. Chickpea is the most common of the puffed legumes (Salunkhe et al., 1985).

3.1.4.3 Modern methods of cooking

Microwave heating: Electromagnetic radiation is classified by wavelength or frequency. Microwaves represent the electromagnetic spectrum between frequencies of 300 MHz and 300 GHz. In contrast to conventional heating systems, microwaves penetrate a food product, and heating extends throughout the entire food material. The rate of heating is therefore more rapid. Microwaves generate heat due to their interaction with the food material. Microwave radiation itself is a non-ionizing radiation. When food is exposed to microwave radiation, no known thermal effects are produced in the food material. The absorption of microwaves by a dielectric material results in the microwaves giving up their energy to the material, with a consequential rise in temperature. The speed of heating of a dielectric material is directly proportional to the power output of the microwave system. Although a high speed of heating is attainable in the microwave field, many food applications require good control of the rate at which the foods are heated. Very high-speed heating may not allow desirable physical and biochemical reactions to occur. Controlling the power output, controls the heating in the microwave. The power required for heating is also proportional to the mass of the product. The composition of food material affects how it heats in the microwave field. The moisture content of food directly affects the amount of microwave absorption. A higher amount of water in a food increases the dielectric loss factor, ε'', which expresses the degree to which an externally applied electrical field will be converted to heat. If the food material is highly porous with a significant amount of air, then due to low thermal conductivity of air, the material will act as a good insulator and show good heating rates in microwaves (Singh and Heldman, 2001). The shape of the food material is important in obtaining uniformity of heating. Non-uniform shapes result in local heating; similarly sharp edges and corners cause non-uniform heating. Heating is a consequence of interactions between microwave energy and a dielectric material. The conversion of microwave energy to heat can be approximated by the following equation (Singh and Heldman, 2001):

$$P_D = 55.61 \times 10^{-14} E^2 f' \in' \tan\delta \tag{3.13}$$

where:

P_D = power dissipation (W/cm^3),

E = electrical field strength (V/cm),

f' = frequency (Hz),

$\in'$ = relative dielectric constant, and

$\tan\delta$ = loss tangent

El-Adawy (2002) reported that microwave cooking resulted in the greatest retention of all minerals followed by autoclaving and boiling. Cooking of chickpea by microwave has not been extensively studied but it has been shown to reduce antinutritional factors and has positive effects on protein digestibility in other legumes. A study on chickpea grains cooked by microwave is thus needed to ascertain whether this treatment could improve nutritional quality and eventually replace traditional cooking or germination which is not only costly in terms of energy but also cause important losses in soluble solids.

Infrared heating: Infrared heating involves the exposure of a material to electromagnetic radiation in the wavelength region of 1.8 to 3.4 μm for biological materials. The penetration of the infrared rays into the material causes the water molecules to vibrate at a frequency of 8.8×10^7 to 1.7×10^8 MHz. This causes rapid internal heating and a rise in water vapor pressure inside the material. Prolonged exposure of a biological material to infrared heat results in the swelling and eventual fracturing of the material (Jones, 1992). Fasina and co-workers (1996) showed that infrared heating changes the physical, mechanical, chemical properties of barley grains. Kouizeh-Kanani and co-workers (1983) and van Zuilichem and van der Poel (1989) reported the effect of infrared heating on the antinutritional factors in soybeans and peas, respectively. The effect on physical and mechanical properties of legume seeds namely, kidney beans, green beans, black beans, lentil and pinto beans when subjected to infrared heating was studied (Fasina et al., 1997; Fasina et al., 2001). In most of the cases, there were increases in the major, minor and intermediate axes when the seeds were infrared heated (Table 3.4). The major axis refers to the longest dimension of the maximum projected area; the intermediate axis refers to the minimum dimension of the maximum projected area or longest dimension of the minimum projected area; and, the minor axis is the shortest dimension of the minimum projected area for seeds.

Table 3.4 Average physical dimension of legume seeds (Fasina et al., 1997).

Legume sample		Major axis (mm)	Minor axis (mm)	Intermediate axis (mm)	Volume (mm^3)
Kidney beans	raw	16.66 ± 0.58	6.12 ± 0.56	8.97 ± 0.49	480.62 ± 67.61
	processed	16.70 ± 0.81	6.46 ± 0.41	9.05 ± 0.42	511.47 ± 52.81
Green peas	raw	6.52 ± 0.34	5.76 ± 0.44	6.19 ± 0.37	122.41 ± 19.23
	processed	6.83 ±0.69	6.03 ± 0.23	6.45 ± 0.33	139.06 ± 18.45
Black beans	raw	8.35 ± 0.90	4.25 ± 0.29	5.97 ± 0.33	110.80 ± 16.37
	processed	9.09 ± 0.49	4.74 ± 0.34	6.38 ± 0.30	144.06 ± 21.32
Lentils	raw	6.82 ± 0.39	2.36 ± 0.14	6.64 ± 0.32	56.05 ± 6.58
	processed	6.87 ± 0.26	2.39 ± 0.14	6.58 ± 0.24	56.74 ± 6.11
Pinto beans	raw	12.52 ± 0.73	5.20 ± 0.46	8.30 ± 0.44	284.21 ± 42.62
	processed	12.56 ± 0.50	5.58 ± 0.39	8.17 ± 0.36	300.95 ± 40.70

Within a duration of 15 s or less, the seeds were heated to a surface temperature of 10ºC. Significant changes in the properties of the seeds in terms of increased volume, lower rupture point and toughness, higher water uptake, and higher leaching losses (when seeds were soaked in water) were obtained in comparison to unprocessed seeds. The changes in the physical and mechanical properties of the seeds were attributed to seed cracking during infrared heating (Fasina et al., 1997).

Interest in the use of infrared heating (micronization) in food processing has increased in the past few years due to recent developments in the design of infrared heaters that offer rapid and economical methods for processing of food products with high organoleptic and nutritional value. The most significant advantage of infrared heating when used for drying is the reduction of drying time. It also helps in efficient heat transfer to the food, and reduces processing time and energy costs and uniform heating is achieved in food products. Cenkowski and Sosulski (1996) investigated the effect of infrared heating on the physical and cooking properties of lentil. They found that cooking time was shortened from 30 to 15 min for lentils adjusted to 25.8% moisture content when infrared heated to 55ºC. Micronization procedure has a theoretical or operational efficiency of 90%, while during practical application, efficiency can reach about 65% (Wray et al., 1996). For a tubular infrared lamp rated at 500 W and 120 V, placed at a distance of 105 mm from peas, the maximum micronization time was 90 s. Increasing the micronization time caused peas to darken and then finally brown or burn. At the same time, the 90 s exposure to infrared light caused the sample to lose about 4% moisture. The micronized peas had approximately 15% increase in moisture uptake during boiling when compared to non-micronized samples. The effect of micronization was more pronounced with the whole peas where particularly after 3 min of cooking, the peak force decreased by 30% in comparison to the non-micronized whole peas. The average toughness of micronized half peas after 3 min of cooking was approximately 20% lower than the toughness of the non-micronized halves (Cenkowski and Sosulski, 1996). Similar studies have not been conducted on chickpea.

3.2 Heat and Mass Transfer

Whenever there is a temperature difference in a medium or between media, heat transfer occurs (Incropera and Dewitt, 1996). The theoretical and empirical relationships utilized in the design of heat processes assume the knowledge of thermal properties of the material which was discussed in the previous sections. Heat transfer between a solid and its surroundings can take place by conduction, convection, and radiation. In some cases, all three forms of heat transfer operate simultaneously (Mohsenin, 1980). Conduction is the mode of heat transfer in which the transfer of energy takes place at a molecular level. Conduction is the most common mode of heat transfer in the heating of opaque solid materials. When a fluid comes in contact with a solid body, heat exchange will occur between the solid and the fluid whenever there is a temperature difference between the two. During heating and cooling of gases and liquids, the fluid streams exchange heat with the solid surfaces by convection. Radiation heat transfer occurs between two surfaces by the emission and later absorption of electromagnetic waves (or photons). In solid foods, the analysis is primarily concerned with the surface of the material. This is in contrast to microwave and radio frequency radiation, where wave penetration into a solid object is significant. A solid food material may be classified as moist, porous, hygroscopic solid with low thermal conductivity. Such materials offer high resistance to internal heat transfer (Adu and Otten, 1996).

Mass transfer plays a key role in food processing. If there are differences in concentrations of constituents throughout a solution or object, there will be a tendency for movement of material to produce a uniform concentration. Such movement may occur in gas, liquid, or solid solutions. Movement resulting from random molecular motion is called diffusion. In solid, there can obviously be no convection and all movement is by molecular diffusion. Mass transfer occurs during various food processing operations like humidification and dehumidification, dehydration, distillation, absorption, etc. The driving force for mass diffusion is the concentration difference. The basic relationship is called Fick's law and can be written as follows (Singh and Heldman, 2001):

$$N_A = -D\left(\frac{dC_a}{dx}\right) \tag{3.14}$$

where:

N_A = mass flux of species A ($kg/s.m^2$),

C_a = concentration in mass per volume,

x = distance in the direction of diffusion, and

D = diffusion coefficient, or diffusivity.

Most of the heat and mass transfer modeling in terms of cooking have been concentrated on specific food and biological products whereas, study on legumes seeds have been limited to drying. Past studies did not take into account the effect of heat and mass transfer characteristics during cooking of legume seeds.

3.3 Mathematical Modeling

Numerical solution techniques are usually easier than analytical techniques since engineering problems involve ordinary or partial differential equations which may not be solved with the analytical solution techniques. In food and bioprocess modeling, the finite difference method is commonly used especially in solving partial differential equations.

The coupling of heat and mass transfer process necessitates the use of numerical techniques to solve heat and mass transfer differential equations simultaneously. The finite difference method (FDM) and the finite element method (FEM) are among the numerical methods that are widely used to solve a system of differential equations (Fasina et al., 1993). Irudayaraj and co-workers (1992) compared the temperature and moisture predictions of different sets of coupled heat and mass transfer models. The application was on the drying of soybean, barley, and corn. They reported that the simulation results from the heat and mass transfer models agreed well with the available experimental results.

A three dimensional non-linear finite element model involving variable diffusion coefficients, thermal conductivities and specific heat was developed by Fasina and co-workers (1993) in an expanding alfalfa cube during moisture adsorption and they reported that the rate of moisture absorption was dependent upon the relative humidity and temperature of the surrounding air.

Huang and Mittal (1995) developed a model, simulated and validated the heat and moisture transfer phenomena within a meatball during different cooking processes to predict the temperature and mass of the meatball. They reported that the average cooking time of meatball, by boiling in water was 770 s. Bengtsson and co-workers. (1976)

studied the heat and mass transfer in beef roasts and reported that there is an inverse relationship between the moisture and temperature histories.

Pavon-Melendez and co-workers (2002) studied the dimensionless analysis of the simultaneous heat and mass transfer in food drying. The theoretical analysis and experimental drying kinetics showed that in mango drying, the temperature evolution was controlled by heat convection in the food-air interface and moisture loss was controlled by water diffusion in the interior of food. Mulet (1994) studied the suitability of heat and mass transfer equations simplifications for modeling the experimental drying kinetics of carrots. He showed that a model with constant temperature and constant diffusivity fitted the drying curves with minimal root mean square deviations. Baik and Mittal (2004) developed mathematical models to describe moisture, fat and heat transfer during deep fat frying of a tofu disc. The model developed was useful for the prediction of temperature, moisture and fat content during tofu frying at different temperatures. They proved that the methodology proposed to incorporate shrinkage is simple and applicable for simulating the frying process of different food products.

Maroulis et al. (1995) modeled air drying of foods with simultaneous heat and mass transfer equations solved numerically. They reported that a model with variable diffusivity, interface resistance for heat and mass transfer, and with heat conductivity negligible yield the optimum fit for potato experimental drying kinetics. A one-dimensional finite difference modeling of heat and mass transfer during thawing of ham was reported by Delgado and Sun (2003) and the results showed that the effect of the uncertainty of thermo-physical properties on the prediction of thawing time was important. A mathematical model using the finite difference technique was developed for simultaneous heat and moisture transfer during drying of potato (Wang and Brennan, 1995). The model took into account the effect of moisture-solid interaction at the drying surface by means of sorption isotherms of food. The model was successfullapplied to the air drying potatoes.

Mathematical models developed so far have considered the transport properties of either moisture or temperature in specific food products using microwave or infrared techniques. Whereas heat and mass transfer properties during boiling of chickpea with water has not been studied. Hence, an extensive study will be useful for further studies being conducted in this area.

3.4 Summary

Research reviewed in this thesis indicated the available data for the physical and thermal properties of chickpea. However, the thermo-physical properties of kabuli type chickpea have not been reported so far. The composition, physical, and mechanical properties of chickpea when subjected to different heat treatment methods was reported. There is a lack of information on the heat and mass transfer characteristics of chickpea and also on modeling of the cooking process. Numerical method for solving the heat and mass transfer equations was discussed.

4. MATERIALS AND METHODS

Food thermal properties play an important role in the quantitative analysis of food processing operations. An overview of the materials used and the experiments that were conducted for the purpose of modeling are explained in this chapter. Measurement of density, thermal conductivity, specific heat, grain temperature during cooking, water absorption during soaking and moisture absorption during cooking are discussed. Solid loss during soaking is also explained.

4.1 Material

Kabuli type chickpea *(Cicer arietinum* L.) were procured from Canadian Select Grain (Eston, SK) and stored in a walk-in cold storage room at 5-7°C, located in the Department of Agricultural and Bioresource Engineering, University of Saskatchewan.

4.2 Moisture Content Determination

Moisture content was determined for randomly selected grain using the AOAC method (AOAC, 2002). Small aluminum pans were used in containing the sample for moisture determination. About 2 to 3 g of Wiley mill-ground samples were taken and weighed. The sample mass before drying was recorded and the sample was placed in the oven at 130°C for 1 to 2 h. The samples were taken out, cooled in a dessicator and then weighed again. The loss of weight in the sample was used to calculate the moisture content of the sample (Equation 4.1); the initial moisture content of the sample was found to be 9.86% w.b. The grains were conditioned to different moisture contents by drying or rewetting them.

$$M_w = \frac{W_w}{W_s} \times 100 \tag{4.1}$$

where:

M_w = moisture content of the sample (% w.b.),

W_w = mass of water (g), and

W_s = mass of the sample (g) before drying.

Dried samples having moisture content of 7% was obtained by drying in a forced-air thin layer dryer at a temperature of 50°C. Rewetted samples ranging in moisture content from 13 to 35% were obtained by spraying pre-determined amounts of distilled water on the chickpea seeds, followed by periodic tumbling of the samples in sealed containers. Grains of moisture content of 55% were obtained by fully soaking the seed in distilled water for 12 h, and that of 65% was obtained by boiling the grains in water. The moisture conditioned grains were stored in the walk-in cold storage room in airtight glass containers for further experiments.

4.3 Density Measurement

Particle density is the density of a sample which has not been structurally modified (Rahman, 1995). It includes the volume of all closed pores but not the externally connected pores. Density is a physical property of a food material dependent both on temperature and moisture content.

This experiment was carried out to determine the particle density of the seed at 7 levels of moisture content, namely 9.86, 13.20, 18.17, 25.10, 35.89, 55.97 and 65.24% w.b., respectively. Density measurement was done in 5 replicates. The instrument used for this experiment was the multipycnometer (Quantachrome Corporation, Boynton Beach, FL) as shown in the Figure 4.1. It is the most versatile model and gained its name from its multiple volume features that offers three sizes of interchangeable sample cells: 135, 20 and 4.5 cm^3. In addition, there are three different calibrated reference volumes which provide peak performance for each cell size. The operating sequence is that the reference volume is pressurized and then the gas is expanded into the sample cell. The very wide operating range of the multipycnometer offers the greatest sample flexibility in the series, while it maintains a degree of accuracy. This instrument is specifically designed to measure the true volume of various quantities of solid materials. The technique employs the Archimedes principle of fluid displacement to determine the volume. The displaced fluid is a gas which can penetrate the finest pores to assure maximum accuracy. For this reason, helium is recommended since its small atomic dimension assures penetration into crevices and pores approaching one Angstrom (10^{-10} m). Its behavior as an ideal gas is also desirable. Other gases such as nitrogen can be used, often with no measurable difference.

Figure 4.1 Multipycnometer used for measuring particle density.

A schematic diagram of the gas multipycnometer is shown in Figure 4.2. It determines the volume of samples by measuring the pressure difference when a known quantity of nitrogen gas under pressure is allowed to flow from a precisely known reference volume (V_R) into a sample cell containing the solid or powdered material.

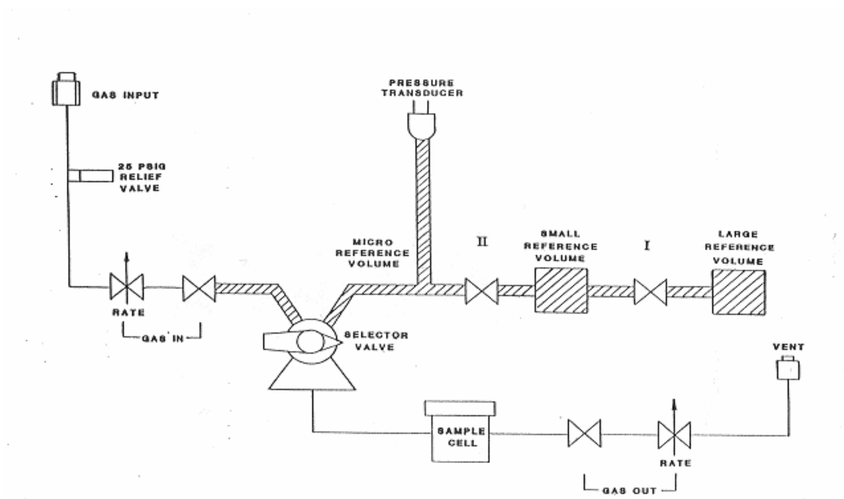

Figure 4.2 Schematic diagram of gas multipycnometer (Manual, Quantachrome Corporation, Boynton Beach, FL)

The working equation is given as follows (Manual, Quantachrome Corporation, Boynton Beach, FL):

$$V_p = V_c - V_R\left[\left(\frac{P_1}{P_2}\right)\right] - 1 \qquad (4.2)$$

where:

V_p = volume of the particle (cm^3),

V_c = volume of the cell (cm^3),

V_R = reference volume for the large cell (cm^3),

P_1 = pressure reading after pressurizing the reference volume (psi), and

P_2 = pressure reading after including V_c (psi).

Prior to measuring the density of a sample, calibration for the pycnometer was done to determine the reference volume of a large calibration sphere. Particle density refers to the weight per unit volume of the grain kernel and was calculated using Equation 4.3:

$$\rho = \frac{m}{V_p} \tag{4.3}$$

where:

ρ = density (kg/m^3), and

m = mass (kg).

4.4 Thermal Conductivity

Thermal conductivity of food is an important property to be considered in calculations involving rate of heat transfer. Materials of high thermal conductivity dissipate heat faster than those of low thermal conductivity. Most high moisture foods have thermal conductivity equal to that of water.

The objective of this experiment was to determine the thermal conductivity of chickpea at 5 different moisture levels, namely 7.00, 9.86, 13.30, 18.17 and 25.10% w.b. at temperatures 25.0, 40.0, 60.0, 80.0 and 98.7°C, respectively. This experiment was conducted in triplicates using two probes, namely, the assembled probe and the thermal properties analyzer.

4.4.1 Thermal conductivity measurement using the assembled probe

Thermal conductivity was determined using an assembled thermal conductivity probe. The line source method was used to measure the thermal conductivity of chickpea.

The unsteady state method uses either a bare wire or a thermal conductivity probe as a heating source, and estimates the thermal conductivity based on the relationship between the sample core temperature and the heating time.

The probe method was used in measuring the thermal conductivity due to its ease of use and accuracy (± 0.05ºC) in measurements. This probe method saves both energy and time. Time taken to take a set of time-temperature data is around 2 min. The single-needle probe technology reduces user error. It is a portable handheld device which can be used in environments maintained at different ambient temperatures. The effects on the thermal conductivity measurement using the probe can be negligibly small if the instrument and the measurement procedure are adequately designed. Fine needle probe is commonly used in determining the thermal conductivity of penetrable materials such as fluids, fruit and animal flesh. The use has been extended in finding the thermal conductivity of seeds.

Correction analysis of the dimension influence on the measurement accuracy of thermal conductivities by transient probe method is made. The radial and axial lengths of the measured sample, the radius ratio and heat capacity ratio of sample to probe, as well as the length to diameter ratio of the probe are important parameters in error analysis.

4.4.1.1 Probe construction

The thermal conductivity probe used in this study was constructed of a brass needle tubing (length of 91.52 mm and diameter of 2.02 mm) with a Type T thermocouple inside the tubing. The tube was filled with high thermal conductivity paste material. Bare constantan wire (diameter 0.1 mm) with insulation stripped at both ends was utilized as the heater wire. A thermocouple wire was inserted into the probe to half its length. The heater wire and the thermocouple wire were insulated from each other. The heater wire was fed through the brass tubing until it emerged from the paste at the opposite end. One end of the heater wire that emerged from the tubing was crimped and soldered to the tip of the tubing. The other end of the heater wire was attached to the power supply. A piece of heat shrink was attached to the end of the tubing to hold the heater and the thermocouple wires in place. A diagram of the assembled probe is shown in Figure 4.3.

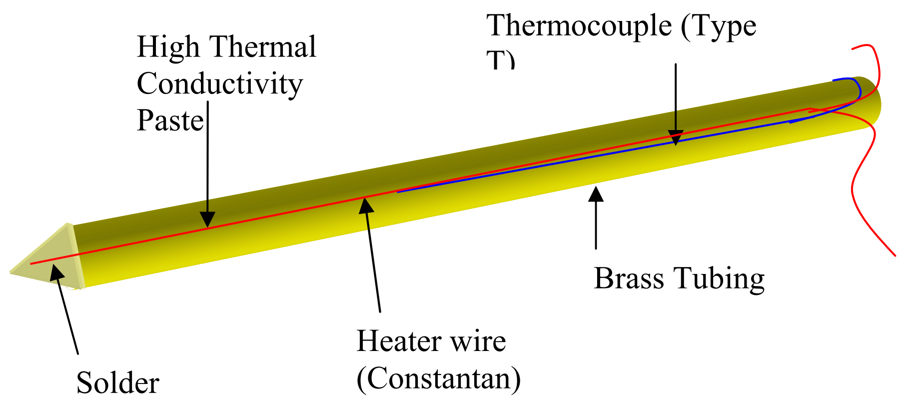

Figure 4.3 Assembled probe for thermal conductivity measurement.

4.4.1.2 Measurement technique for assembled probe method

This method utilizes a constant heat source to an infinite sample body at a uniform initial temperature along a line of infinitesimal diameter compared to the sample body. Having the heat source imbedded in the sample, the line-source is energized and the temperature rise at a given distance from the source is measured after a short heating time. The maximum slope method of arriving at the thermal conductivity (k) values was used (Wang and Hayakawa, 1993). This method involves finding the local slope (temperature rise over ln (time)). The probe was calibrated in distilled water at room temperatures of 23 to 24ºC.

A schematic diagram of the instrumentation for measuring thermal conductivity is shown in Figure 4.4. The components of the system for thermal conductivity measurement consisted of the power supply, thermal conductivity probe and the datalogger. The heater wire of the probe was connected to the power supply and the thermocouple wire was connected to the datalogger. The time-temperature data was monitored using the datalogger which was collected using the system.

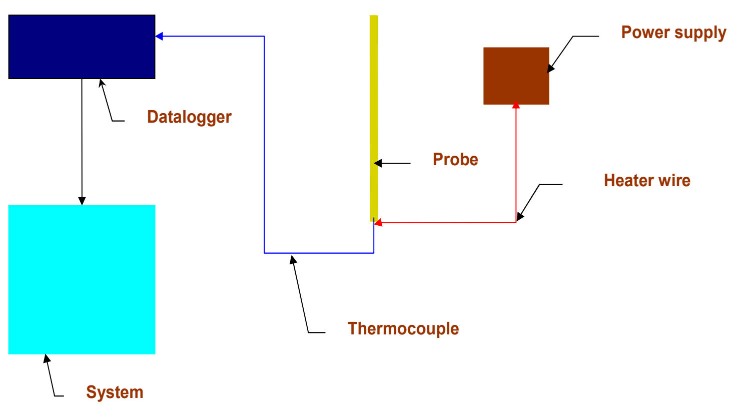

Figure 4.4 Schematic diagram of the thermal conductivity measurement**.**

In principle, the heat generated in a hot wire at a rate q (W/m) is given by:

$$q = I^2R \tag{4.4}$$

where:

I = electric current (A), and

R = electric resistance (Ωm^{-1}).

Equation 4.5 shows a linear relationship between ($T - T_o$) and ln (t) where $\frac{q}{4\pi k}$ is the slope (Yang et al., 2002).

$$T - T_0 = \frac{qA}{2\pi k} - \frac{q}{2\pi k}\ln\left(\frac{1}{2} r\alpha^{-\frac{1}{2}}\right) + \frac{q}{4\pi k}\ln(t) \tag{4.5}$$

where:

T = sample temperature anywhere in the cylinder (°C),

T_0 = initial sample temperature (°C),

t = time (s), and

r = radial axis (m),

Slope S can be obtained from linear regression, and the ($T - T_o$) versus ln (t) and thermal conductivity can then be calculated from S:

$$k = \frac{I^2 R}{4S} \tag{4.6}$$

Due to non-ideal conditions during the experimental trials, such as non-zero mass and volume of the hot wire, heterogeneous and anisotropic properties of biological materials, finite sample size and axial heat flow (Mohsenin, 1980; Suter et al., 1975; Wang and Hayakawa, 1993), temperature rise ($T - T_o$) versus ln(t) does not always follow a linear regression relationship. This calls for correction during data analysis. The most used early method for data correction was the time-correction factor method (van der Held and van Drunen, 1949), which minimized the non-linearity of the ($T - T_o$) versus ln (t) curve by subtracting a factor from the time elapsed. Underwood and McTaggart (1960) proposed a method for time correction for finite probe diameter using the following equation:

$$k = \frac{I^2 R \times 3.414}{4\pi k(T_2 - T_1)} \times 2.3 \log\left(\frac{t_2}{t_1}\right) \tag{4.7}$$

where:

T_2 and T_1 = temperatures (°C),

t_2 and t_1 = time (s).

Equation 4.7 is the corrected equation for a probe with finite diameter. Murakami and Okos (1988) proposed a method for a maximum coefficient of determination (R^2) for the correction, which searched for a maximum linear portion of the curve by successive linear regression using R^2 values as the criteria for the maximum linearity. Wang and Hayakawa (1993) theoretically and experimentally verified the maximum slope method that was first used by Asher et al. (1986). This method calculates the thermal conductivity using the maximum slope around a plateau of the local slope versus ln (t) plot. The study of Wang and Hayakawa (1993) showed that the thermal conductivities determined using the maximum slope method is comparable or more accurate than the time-correction method and the maximum R^2 method.

4.4.1.3 Thermal conductivity of distilled water

The probe was calibrated in distilled water at room temperatures of 23 to 24ºC. A 1 L beaker was filled with distilled water and the probe to be calibrated was held in place. The test was run for 40 to 50 s and the temperature was recorded every 0.25 s in the Campbell Scientific CR10X datalogger (Campbell Scientific, Inc., Logan, UT). Three trials were done for each temperature. The maximum slope method of arriving at the thermal conductivity (k) values was used (Wang and Hayakawa, 1993). The maximum slope was identified and the thermal conductivity as shown in Equation 4.8 was calculated. For distilled water measurements, the local slope was determined by linear regression analysis of around 20 values of ln (time) (x) and the temperature (y). A k value determined by this method is the average temperature of the maximum line segment with a temperature increase around this segment of less than 0.5ºC.

4.4.1.4 Thermal conductivity measurement of chickpea

Holes were bored on the chickpea using a drill bit. The diameter of the drill bit was selected such that it was nearest to the diameter of the probe. Around 8 chickpea seeds were inserted into the probe. Precautions were taken to assure the best contact possible between the chickpea seeds and probe. Fortes and Okos (1980) found the thermal conductivity of corn kernels using the probe method. They applied nail polish between the kernels and on any visible metallic spot in order to prevent any undesirable conduction. In this experiment, the probe with chickpea sample was vacuum packed in a polyethylene bag and assumed to have negligible contact resistance. Figures 4.5 and 4.6 show the chickpea seeds during measurement of thermal conductivity. The grains when tested for thermal conductivity at different temperature ranges were allowed to equilibrate in the respective chamber before the experiments were conducted. The wires connecting the heater in the probe were plugged to a power supply set to a constant current supply of 0.665 A. Temperature data was recorded at every 0.25 s interval on the datalogger (Campbell Scientific, Inc., Logan, UT). The probe resistance was measured to be 5 Ωm^{-1}. The temperature of the chamber was recorded by another thermocouple connected to the data logger at 0.25 s interval.

Figure 4.5 Thermal conductivity probe with chickpea seed sample.

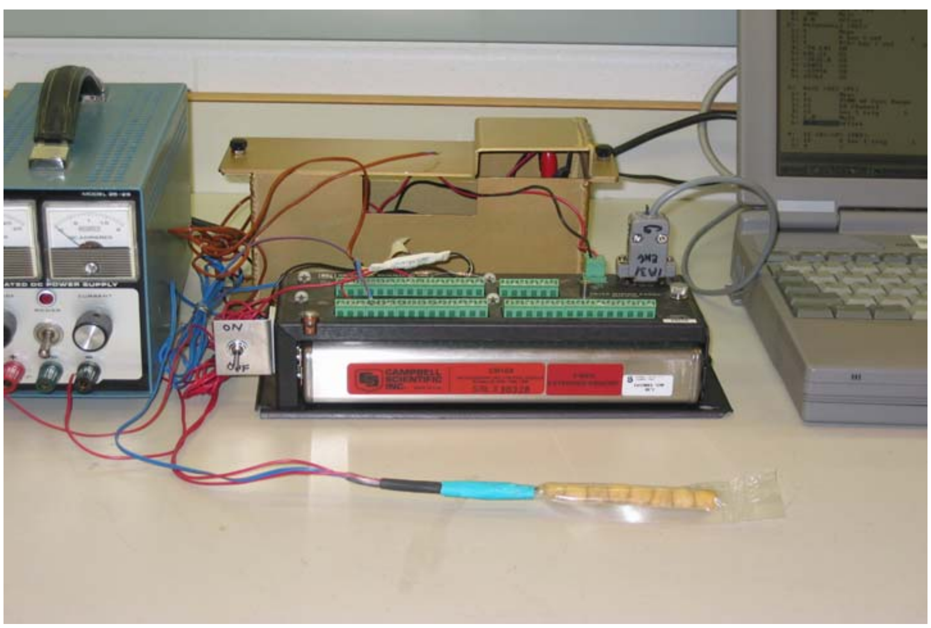

Figure 4.6 Measurement of thermal conductivity of chickpea.

The maximum slope method described previously was used to calculate the thermal conductivity of chickpea. Local slope was determined by linear regression analysis of 20 values of ln (time) (x) and probe temperature (y). The k value was calculated using Equation 4.8 with the maximum slope calculated earlier.

$$k = \frac{q'}{4\pi k(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \tag{4.8}$$

where:

$q' = I^2R$ which is the heat input per meter length of the line source (W/m),

k = thermal conductivity (W/mK) of the medium infinite in size surrounding the heat source,

T = temperature (°C), and

t = time (s),

subscripts:

1 and 2 refer to any two points on a straight line resulting from the plot of temperature versus ln (time).

4.4.2 Thermal conductivity measurement using the KD2 Thermal properties analyzer

The thermal conductivity of the chickpea was also measured using the KD2 thermal properties analyzer (Decagon Devices, Inc., Pullman, WA) for temperatures other than freezing, as its operating temperature was 5 to 35ºC. Figure 4.7 shows the measurement of thermal conductivity of chickpea using the analyzer.

The probe length was 60 mm and its diameter was 0.90 mm Calibration of the probe was done at temperatures of 20, 23 and 24ºC. This analyzer gives direct readings of the thermal conductivity.

Figure 4.7 Measurement of thermal conductivity using the KD2 thermal properties analyzer.

4.5 Specific Heat

Specific heat is an essential property in the thermal analysis during food processing such as heating or cooling of foods. With food materials, this property is a function of its chemical composition, moisture content, temperature and pressure. In most food processing applications, specific heat at constant pressure is used since pressure is generally kept constant except in high pressure processing.

Specific heat was measured at seven levels of moisture content, namely 9.86, 13.20, 18.17, 25.10, 35.89, 55.97 and 65.24% w.b., respectively. Measurements were done in triplicates for each moisture level. It was determined using two methods namely, the indirect mixing method and the differential scanning calorimetry (DSC).

4.5.1 Assembled calorimeter

The principle of indirect mixing method is used in the assembled calorimeter experiment. This method provides no direct contact between the sample and the calorimetric fluid, thus, eliminating the heat of solution of dissolvable chemical entities of food. The specific heat measured using the assembled calorimeter is only a function of moisture content and not a function of temperature, since average temperature (equilibrium temperature) is used. In this measurement, the sample is initially at low temperature and the calorimetric fluid is at a high temperature.

4.5.1.1 Apparatus

The calorimeter consisted of two stainless steel dewar flasks (Cole Parmer Instrument Co., Vernon Hills, IL). The assembled calorimeters are shown in Figures 4.8 and 4.9. Rubber seal rings were attached to the rims of the flask to provide a good seal. The calorimeters were referred to as A and B. Calorimeter A had copper constantan (type T) thermocouples attached to either side of the walls to measure the temperature of the walls as well as the fluid.

Figure 4.8 Assembled calorimeters A and B.

Figure 4.9 Dewar flask with thermocouples attached.

In Figure 4.10, F_1, F_2, and F_3 denote the thermocouple positions measuring the temperature of the fluid, whereas W_1, W_2, and W_3 denote the thermocouple positions measuring the temperature of the walls of the calorimeter A. This kind of thermocouple arrangement was made on either sides of the dewar flask A, named as ‘A’ side and ‘B’ side. The cover for the flasks consisted of inner plexiglass lids with rubber O-rings, and outer cork lid for better insulation with a small opening to let in the thermocouple wire which measures the temperature of the sample.

The thermocouples were connected to the Campbell Scientific CR10X datalogger (Campbell Scientific, Inc., Logan, UT) to collect and record the data. Figure 4.11 shows the special kind of packing gland that was used to insert the thermocouples inside the samples. A Type-T thermocouple was placed inside the plastic screw shown in Figure 4.11. The wire was then sealed to the plastic screw with the help of epoxy (Devcon Corporation, Wood Dale, IL) and clear silicone (Permatex Inc., Salon, OH) and allowed to set for 12 h. These glues were water proof and very good sealants. This thermocouple was then inserted into the nylon polyethylene bag through a small hole which was made with the help of a solder, where the other end was connected to the datalogger. While measuring the temperature for the samples one end of the thermocouple was connected to the centre of the chickpea and the other end to the datalogger. The samples were held inside calorimeter A during temperature measurements by suspending the sample pouch along with the thermocouple wires into calorimeter A.

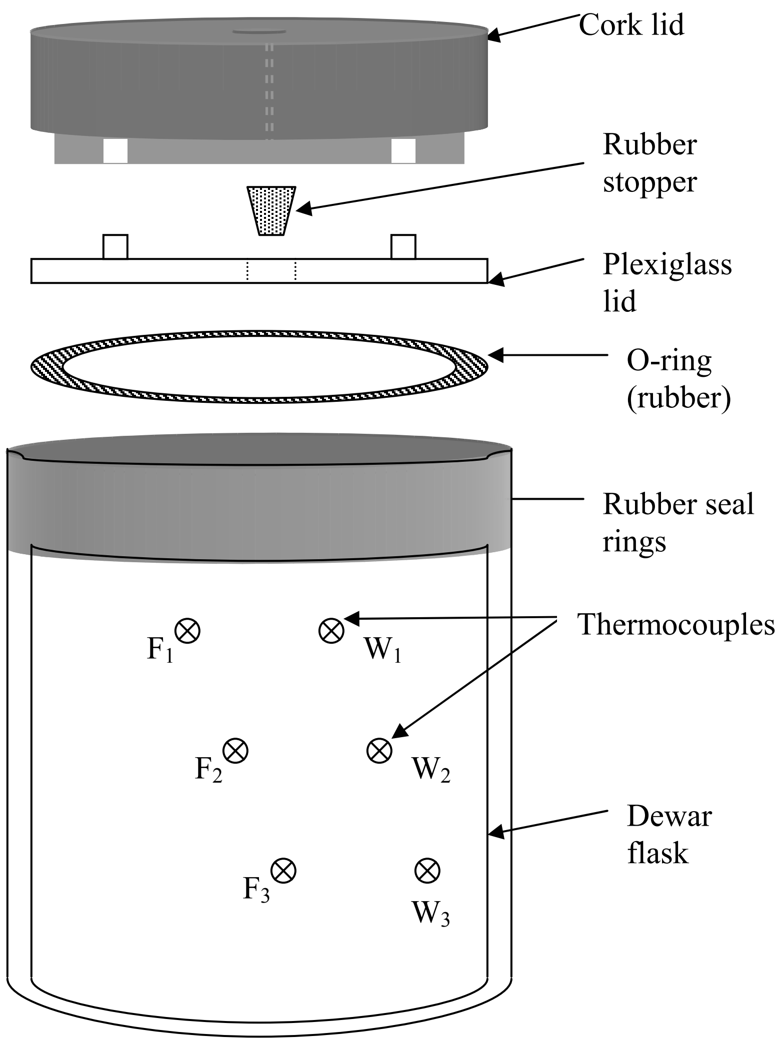

Figure 4.10 Diagram of the calorimeter used for measuring specific heat of chickpea.

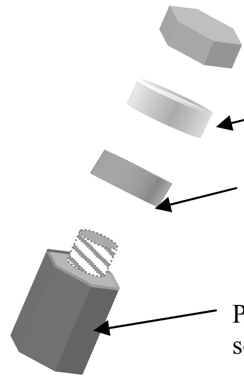

Figure 4.11 Packing gland used to insert thermocouples into the nylon polyethylene bag.

Calorimeter B was another dewar flask with similar type of lids as calorimeter A, except that it did not have the thermocouples attached to the flask. Calorimeter B was used in order to keep water at a constant temperature which in turn was poured into calorimeter A during specific heat measurements.

4.5.1.2 Heat capacity measurement of calorimeter

The heat capacity of the calorimeter was determined prior to measurement of specific heat of the samples. Calorimeter B was filled with deionized water at 50°C and it was placed in a chamber maintained at 37±1.5°C for 15-30 min. The calorimeter was closed to prevent evaporation. Calorimeter A was prepared with a plastic pouch attached with three thermocouples connected to the datalogger. When calorimeter B and the water inside it achieved a constant rate of exchange with its environment, it was taken out and the water was poured into calorimeter A. The datalogger was started when the water from calorimeter B was poured into calorimeter A. Calorimeter A was sealed tightly and shaken every 2 or 3 min. Figure 4.12 shows the setup during heat capacity measurements.

Figure 4.12 Experimental set up during heat capacity measurement.

After 30 min, the data logger was stopped and the weight of calorimeter A with and without water was measured. The calorimeter, plastic pouch and the thermocouples were thoroughly dried before measuring their dry mass. The mass of water used is m_w. From the time-temperature curve, along with the initial temperatures of calorimeter and water, the heat capacity of the calorimeter was calculated using the following equation:

$$H_c = \frac{c_{pw}\, m_w \left(T_e - T_{ow} - \frac{dT}{dt} t_e\right)}{T_{oc} - T_e + \frac{dT}{dt} t_e} \tag{4.9}$$

where:

H_c = heat capacity of calorimeter (kJ/K),

c_{pw} = specific heat of water (kJ/kgK),

m_w = mass of water (kg),

T_e = temperature of water when it reaches equilibrium with the calorimeter (K),

T_{oc} = initial temperature of the calorimeter (K),

T_{ow} = initial temperature of water (K),

dT/dt = rate of temperature change (from graph of time temperature) (K/min), and

t_e = time (min) when water reaches equilibrium with the calorimeter.

4.5.1.3 Specific heat measurement of chickpea using the assembled calorimeter

In this measurement method, whole chickpea seeds were used. It is the intent to use the whole seeds because the characteristic changes of the whole chickpea seed is considered when subjected to cooking. 50 g of chickpea seeds were placed inside a polythene pouch which had three thermocouples attached to it and they were vacuum packed in a single layer with the thermocouples inserted inside the seed at different locations. The thermocouples were inserted inside the seed by boring small holes to the center of the chickpea and the wires were glued to the seed with 5 min curing epoxy. Figure 4.13 shows the sample in the pouch and Figure 4.14 shows the photograph of the calorimeter during specific heat measurement of chickpea.

Figure 4.13 Sample in plastic pouch with thermocouples.

Figure 4.14 Pouring water from calorimeter B to calorimeter A during specific heat measurement.

Prior to measurements, the packed pouches were stored in the refrigerator at 4°C. The datalogger was started as the pouch with chickpea samples was dropped into the calorimeter. From the time temperature curve obtained the specific heat of the sample was calculated using Equation 4.10.

$$c_p = \frac{H_c\left(T_{fc} - T_{oc} - T_R\right) + c_{pw} m_w \left(T_{fw} - T_{ow} - T_R\right)}{m_s\left(T_{os} - T_{fs} + T_R\right)} \tag{4.10}$$

where:

T_{ow}, T_{fw} and T_{2w} = temperatures measured at t_o, t_1 and t_2 assuming that

$$T_{fw} = T_{fc} = T_f \tag{4.11}$$

and

$$T_{fw} = T \tag{4.12}$$

$$T_R = \left(\frac{dT}{dt}\right) t_1 \tag{4.13}$$

thus T_R is calculated from

$$T_R = \frac{T_{2w} - T_{fw}}{t_2 - t_1} \tag{4.14}$$

According to Peralta et al. (1995), the choice of t_1 and t_2 are critical in estimating the values of T_R. The value of t_1 was taken when the temperature of the water in the calorimeter and that of the sample were within ±0.1°C from each other for the first time and the value of t_2 was taken 5 min after measuring t_1.

4.5.2 Differential scanning calorimetry

The differential scanning calorimetry method was also used to determine the specific heat of chickpea. Due to limited access of this instrument, only one set of readings was taken for each level of moisture content. In this method, moisture and temperature were considered as independent variables affecting the specific heat. This method is based on measuring very small thermal effects produced in thermal processes. The recorder in the system produces a thermogram showing any gain or loss of energy as the sample is scanned at a given rate of temperature rise over a selected temperature interval. The area inside the thermogram is proportional to the heat energy absorbed or released by the sample during the heating or cooling process.

4.5.2.1 Apparatus

The differential scanning calorimetry (DSC) experiment described in this thesis was performed using a temperature modulated DSC 2910 (MDSC^{TM}, TA Instrument Inc., New Castle, DE) using a liquid nitrogen cooling accessory and a nitrogen gas DSC cell purge. The DSC 2910 system allows both heating and cooling scans in the modulated or non-modulated DSC regime. The DSC is a comparative device and must be calibrated.

The instrument was calibrated for specific heat capacity (c_p) with sapphire as standard reference. The reference value for c_p was obtained from the manufacturer. Due to limited access of instrument it was not calibrated with water. The data analyzer was Thermal Analyst 2100 (TA Instruments, Inc., New Castle, DE).

4.5.2.2 Sample preparation for measurements

Sample moisture contents ranging between 18.17% and 55.97% w.b. were obtained by soaking whole seeds with predetermined amount of distilled water. The sample moisture content of 65.24% w.b. was obtained by fully cooking the seed. The conditioned chickpea seeds were ground with the help of a blender, stored in small airtight bottles and were allowed to equilibrate in the cold storage room at 5 to 7°C for one week before measurements. Ground samples were used because the DSC was capable of measuring the heat capacity for small quantity of sample ranging from 10-20 mg.The powdered samples prepared were at 6 levels of moisture content, namely 9.86, 18.17, 26.54, 37.89, 55.97 and 65.24%.

4.5.2.3 Specific heat measurement by the DSC

The DSC includes two heating discs which are in thermal contact with one another and are isolated from the environment. Figures 4.15 and 4.16 show the photographs of the DSC used and the sample holder, respectively. Two pans, in which, one of the pans contains a sample and the other is an empty reference pan, were placed on the discs in the holder.

Prior to testing, approximately 10 to 20 mg of sample was weighed and placed in one of the small pan. This was hermetically sealed and dusted using a pressurized duster. Heating both pans at a controlled, known rate and measuring the heat flow between them, gave the differential in heat capacity of the reference pan and the sample.

Figure 4.15 Differential scanning calorimeter**.**

Figure 4.16 DSC sample holder.

Figure 4.17 shows the schematic of the DSC measurement. Figure 4.18 shows the ground samples and the samples sealed in small aluminum pans.

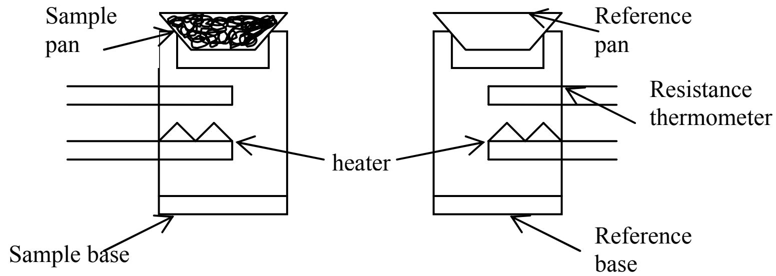

Figure 4.17 Schematic of the DSC for specific heat measurement.

Figure 4.18 Ground samples and samples sealed in pans.

For specific heat measurements, the instrument raises the temperature of the sample in the DSC cell at a constant heating rate. The heat flow rate into the sample is determined according to the following equation (Widmann and Riesen, 1987):

$$c_p = \frac{dQ/dt}{mdT/dt} \tag{4.15}$$

where:

c_p = heat capacity (kJ/kgK),

dQ/dt = heat flow rate (J/s),

dT/dt = heating rate (K/s), and

m = mass of the sample (g).

The temperature of the sample in the DSC cell increased at a constant heating rate for measuring the specific heat of food. Factors that can affect the measured values of biological materials are sample size, heating rate and sample sealing. The determination of the specific heat using DSC is based on the assumption that during the test, the temperature is uniform in the sample and the sample container. Temperature rise during a DSC test increases the vapor pressure within the sample and as a result, moisture may escape from the biological material in the form of water vapor. The latent heat absorbed in the process may introduce error in the measurement. Thus, encapsulation or sample pan sealing must be used to get good results (Mohsenin, 1980; Tang et al, 1991).

4.6 Thermal Diffusivity

The physical significance of thermal diffusivity is in determining how fast heat propagates or diffuses through a material. The main application of thermal diffusivity is to estimate the thermal processing time. It is a measure of the quantity of heat absorbed by a material for a given temperature change, and further indicates the ability of the material to conduct heat to adjacent molecules. The thermal diffusivity of chickpea was calculated using the experimental values of specific heat, thermal conductivity and density values from the following equation:

$$\alpha = \frac{k}{\rho\, c_p} \tag{4.16}$$

where:

k = thermal conductivity (W/mK),

ρ = particle density in (kg/m^3), and

c_p = specific heat of the chickpea (kJ/kgK).

The density values were obtained by experimentally determining the particle density of the chickpea at different moisture contents using the gas pycnometer mentioned earlier in this chapter.

4.7 Water Absorption During Soaking

This experiment was conducted to understand the moisture absorption characteristics of chickpea grain at temperatures ranging from room temperature (24°C) to cooking temperature namely 45, 60, 80, 98.7°C. Before each experiment, the samples, containers and distilled water were kept in the desired temperature for a few hours to reach to equilibrium. Samples were randomly hand selected excluding foreign materials and broken, cracked and damaged grain. Ten grains were selected and weighed, then placed in a glass beaker containing 200 ml distilled water. After every 1 h, the grains were removed from the beakers and dried on a paper towel to absorb the excess water on the surface and the mass loss was measured with the help of an electronic weighing balance, and then returned to the beaker. The duration and the mass of the samples were recorded manually. An experiment was terminated when the grain mass attained an equilibrium value, that is when the incremental change in the sample mass was less that 0.001 g when measured after 1 h of soaking. Tests were done in three replicates.

4.8 Moisture Diffusivity Measurement During Cooking

Moisture diffusivity is an important transport property necessary for the design and optimization of all the processes that involve internal moisture movement. This experiment was conducted at cooking temperatures to determine moisture diffusion during cooking of chickpea at temperatures of 70, 80, 90, and 98.7°C. Chickpea samples of initial moisture content 9.86% and 55% w.b., were used. Prior to the experiments, the samples were kept in the cold storage room.

4.8.1 Measurement of moisture diffusivity

The heat source was a thermostatically controlled hotplate. Distilled water (500 ml) was filled in an aluminum pan of diameter 21.5 cm and height 24.5 cm and heated by the hotplate. Water temperature was maintained constant. 100 g of chickpea grain was taken and soaked in the water. After every 1 h of soaking, the seeds were retrieved from the pan, placed on tissue towel to remove excess water on the surface and placed in plastic pouches and stored in the cold storage room for moisture content measurement. This process was repeated until the seeds were cooked.

Moisture flow within a grain kernel takes place by diffusion. The transfer coefficient is called as diffusion coefficient. Moisture diffusivity value was obtained by applying Fick's second law for species diffusion in a single phase, with boundary conditions of internal resistance controlling uniform moisture content, integrated over the volume of the slab (apple, mango) or sphere (strawberry) (Luikov, 1968). Moisture diffusivity for a spherical grain with radial symmetry was calculated using the following equation:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{n^2\pi^2}{9}X^2\right] \quad (4.17)$$

In the above equation, the average moisture content and the time are expressed as dimensionless quantities.

where:

MR = moisture ratio, and

X = dimensionless time as shown in the following equations:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (4.18)$$

and

$$X = \frac{A}{V}(Dt)^{\frac{1}{2}} \quad (4.19)$$

where:

M = moisture content of chickpea at time t during cooking (dry basis (% or decimal)),

M_i = initial moisture content (dry basis (% or decimal)),

M_e = equilibrium moisture content (dry basis (% or decimal)).

A = surface area (m^2),

V = volume of the kernel (m^3),

A/V=3/radius for a sphere, and

D = diffusion coefficient (m^2/h).

4.9 Temperature Measurement in the Center of Chickpea

This experiment was conducted in order to measure the cooking time of the chickpea and also to determine the temperature at the center of the seed during cooking.

This data was used in verifying the modeling results. This experiment was conducted at temperatures of 70, 80, 90 and 98.7°C at two levels of sample moisture contents namely, 9.86% and 55% w.b., for the unsoaked and soaked grain, respectively.

4.9.1 Sample preparation

Chickpea of uniform size of approximately 10 mm diameter were taken from the cold storage room and selected randomly. This experiment was conducted in triplicates for both soaked and unsoaked grain. Soaked grains were obtained by soaking the chickpea grains for 12 h at room temperature in airtight containers in the cold storage room, prior to experiments.

4.9.2 Temperature measurement

In order to measure the temperature of the centre of chickpea grain, a small hole was made using a drill bit to the centre of the grain. Thermocouples that were used for measuring the centre temperature of chickpea were of 0.5 mm in diameter copper-constantan wires (Type T) encased in Teflon tubing. They were further connected to thermocouple wires of bigger diameter. One end was glued to the centre of the grain and the other end was connected to the CR10X datalogger (Campbell Scientific, Inc., Logan, UT). Three seeds were selected randomly for each run of experiment. The thermocouples were inserted in the bored holes and they were sealed with epoxy and silicon glue and left for 24 h to dry. To prevent moisture evaporation, they were sealed in plastic pouches. Heat source was a hotplate which was controlled with a thermostat and the pan used was made of aluminum having a diameter of 21.5 cm and a height of 24.5 cm. Distilled water was filled in the pan and heated. The water temperature was maintained constant to within ± 0.05°C. Two instrumented chickpea seeds were suspended in the water and cooked along with 100 g of chickpea. They were cooked without lid. Temperature data was recorded with time with the help of the datalogger. Periodically, a chickpea seed were removed with the help of a small strainer and squeezed with the help of fingers to see if they were cooked. Once the grains were cooked, they were removed. This experiment was repeated for different temperatures namely 70, 80, 90 and 98.7°C for both the unsoaked and soaked grain.

4.10 Solid Loss During Cooking

This experiment was conducted to determine the mass loss during soaking and cooking of chickpea. It was conducted at temperatures of 25, 40, 60, 80, 98.7°C.

4.10.1 Solid loss measurement

Samples with initial moisture content 9.86% were used, and approximately 25 g of grain were weighed for each experiment. For this experiment, a 500 ml glass dish was used. The mass of the empty dish was recorded prior to adding water. Water (200 ml) was poured into the dishes and the dish was placed in the chamber to maintain a constant temperature and the previously weighed grain was soaked in the dish for 12 h. Soaking at 25, 40 and 60°C were done in chambers maintained at these required temperatures; and the cooking temperatures of 80 and 98.7°C were obtained by placing the container in the hotplate controlled with a thermostat. After 12 h, the soaked and cooked grains were removed, the remaining water and the solids were evaporated at low temperatures and the mass was taken. The mass difference of the dish with the dried mass and the empty dish was considered as the amount of solid loss during soaking and cooking. Figures 4.19 and 4.20 show the soaking of grain and the evaporated solids in the dish after removal of the grain, respectively.

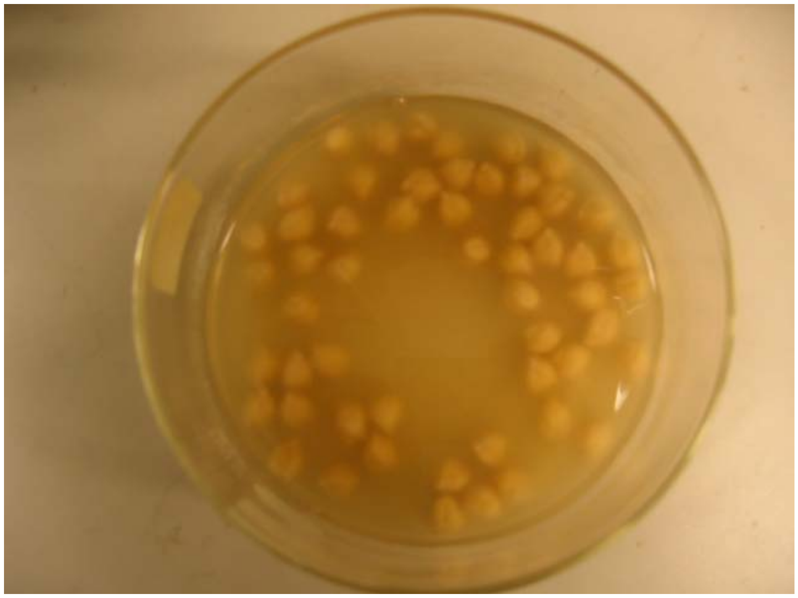

Figure 4.19 Soaked chickpea.

Figure 4.20 Solid loss during soaking.

5. MODELING AND SIMULATION

In this chapter, the partial differential equations for temperature and moisture distribution used for the modeling and the finite difference formulation and the solution methodology to obtain the result are explained. A brief detail of the simulation program is also mentioned.

This chapter reviews the modeling of the cooking process. Finite difference method was used to solve the mathematical equations and simulation was carried out using suitable software, the Interactive Simulator (ISIM) Rev 2.06 simulation programming (Dunn et al., 1992). In the context of food processing, a mathematical model involves an approximate representation of a process in mathematical terms. In many cases, such as in biological systems, where the material is a poor conductor of heat, the mathematical model for a real time system cannot be solved analytically, thus, computer simulation is used. This is best characterized with the Biot number which provides a measure of the temperature drop in the solid relative to the temperature difference between the surface and the fluid. The solutions to these equations are supposed to simulate the natural behavior of the material.

Cooking is an important form of heat treatment in the food industry because of such advantages as simplicity of equipment and consumer preference. Factors such as raw material, cooking time of the grain, and the initial moisture content of the sample will affect the final product temperature and moisture content. The optimum combination of these factors can be obtained by complete experimentation or by use of computer modeling and simulation with subsequent verification of the models by experimental results.

Heat may be transferred by one or more of the three mechanisms of conduction, convection and radiation. Figure 5.1 shows the directions of heat and mass flow during cooking of chickpea based on the assumptions mentioned below.

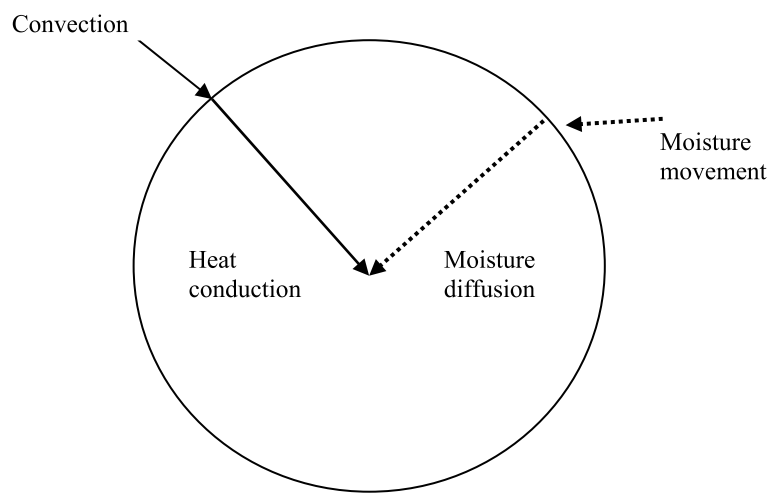

Figure 5.1 Direction of heat and mass flow during cooking of chickpea

5.1 Assumptions in Modeling

The following assumptions were made:

1) heat and moisture transfer is one dimensional, unsteady state in the radial direction;
2) chickpea is considered to be an almost spherical object;
3) the initial temperature and moisture distributions are uniform;
4) there is a temperature and moisture gradient in the chickpea with respect to time;
5) the thermal properties are constant;
6) chickpea is considered as a homogeneous isotropic solid;

7) heat is transferred to the surface by convection and to the geometric center of the seed by conduction;
8) moisture transfer to and from the seed is due to concentration gradient;
9) the amount of solid loss in the grains during cooking was neglected.

Based on the above assumptions, the mathematical models characterizing one dimensional heat and moisture transfer in a chickpea grain during cooking was investigated.

5.2 Governing Equations and Boundary Conditions for Heat and Mass Transfer

The system of equations and the associated initial and boundary conditions used to describe the heat and moisture transfer process in the cooking of chickpea seeds, based on the assumptions made above are given in the following subsections.

5.2.1 Heat and mass transfer

In food process engineering, heat transfer is very often in the unsteady state, in which temperatures are changing and materials are warming or cooling. Unfortunately, the study of heat flow under these conditions is complicated. There are some cases that can be simplified and handled by elementary methods, and charts have been prepared which can be used to obtain numerical solutions under some conditions of practical importance. A simple case of unsteady-state heat transfer arises from the heating or cooling of solid bodies made from good thermal conductors.

Heat transfer is the process whereby heat flows from regions of higher to regions of lower temperature. Unsteady-state (or transient) heat transfer is that phase of the heating and cooling process when the temperature changes as a function of both location and time. In food process operations, the unsteady-state period is an important component of the process. Analysis of temperature variations with time during the unsteady-state period is essential in designing such a process.

Temperature is a function of two independent variables, time and location, hence the following partial differential equation is the governing equation for a one dimensional case.

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p r^n} \frac{\partial}{\partial r}\left(r^n \frac{\partial T}{\partial t} \right) \tag{5.1}$$

where:

T = temperature (°C),

t = time (s),

r = the distance from centre location (mm).

Equation 5.1 can be expressed for different geometrical shapes using

n = 0 for slab,

n = 1 for cylinder, and

n = 2 for sphere.

The combination of properties $k/\rho c_p$ is defined as thermal diffusivity, α. The general equation of heat transfer at a constant α for a spherical object is given as

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) \tag{5.2}$$

where:

α = thermal diffusivity (m^2/s).

Diffusion is the process by which matter is transported from one part of a system to another as a result of random molecular motions. General solutions of the diffusion equation can be obtained for a variety of initial and boundary conditions provided the diffusion coefficient is constant. If the diffusion is radial, the diffusion equation for a constant diffusion coefficient in a spherical system takes the form of:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial r^2} + \frac{2}{r}\frac{\partial C}{\partial r}\right) \tag{5.3}$$

where:

D = diffusion coefficient (m^2/s),

C = concentration (kg/kg), and

r = radial distance from the center of the seed (m).

5.2.2 Initial and boundary conditions

The boundary conditions are specified at the center and surface r = 0 and $r = r_0$ for a one dimensional system. Heat transfer is in the positive radial direction with temperature distribution, which may be time dependent designated as T(r, t). The first condition corresponds to a situation for which the surface is maintained at a fixed temperature, T_s, since the surface is in contact with the boiling liquid.

The initial temperature and moisture distribution are assumed to be uniform. The initial condition for the distribution of temperature is specified as:

$$T(r,0) = T_0 \tag{5.4}$$

at the center for symmetric heating condition:

$$\left.\frac{\partial T}{\partial t}\right|_{r=0} = 0 \tag{5.5}$$

Due to heat transfer at the surface of the seed by convection and to the geometric center of the seed by conduction the boundary condition for heat transfer is given by the following equation (Huang and Mittal, 1995):

$$k\left.\frac{\partial T}{\partial r}\right|_{r=R} = h(T_a - T_s) \tag{5.6}$$

where

h = heat transfer coefficient (W/m^2K),

T_a = ambient water temperature (K), and

T_s = surface temperature of the chickpea (K).

The initial and boundary condition for the movement of moisture is given as:

$$M(r,0) = M_0 \tag{5.7}$$

at the center:

$$\left.\frac{\partial M}{\partial t}\right|_{r=0} = 0 \tag{5.8}$$

Convective mass transfer was assumed to be negligible since no external force was used to stir and enhance the cooking process. Moisture content at the surface of the chickpea seed was assumed to be in instantaneous equilibrium with that of the environment (Huang and Mittal, 1995; Williams and Mittal, 1999; Ateba and Mittal, 1994). In this surface convection condition, if the mass transfer Biot number is much larger than unity, the resistance to mass transfer by diffusion is much larger than the resistance to transfer by convection. Taking this situation into account, the surface concentration of the seed may be replaced by the concentration of the cooking medium (water) Incropera and DeWitt (1996).

The boundary condition of the moisture content equilibrium of the chickpea surface with the boiling water is expressed by (Huang and Mittal, 1995):

$$M\Big|_{r=R} = M_0 \ \text{at} \ t>0 \tag{5.9}$$

$$M_s = M_e \tag{5.10}$$

where:

M_s = moisture content at the surface of chickpea (dry basis (%) or decimals)

M_e = equilibrium moisture content at the surface of chickpea (dry basis (%) or decimals)

Due to diffusion and convection at the surface, mass transfer equation is given as:

$$D_m \frac{\partial M}{\partial r}\Big|_{r=R} = h_m (c_w - c_s) \tag{5.11}$$

where:

D_m = diffusive mass transfer coefficient (m^2/s),

h_m = surface mass transfer coefficient (m^2/s),

c_s = concentration of water in the seed (kg/m^3),

c_w = concentration of water (1000 kg/m^3), and

M = moisture concentration (kg/kg).

5.3 Non-dimensional Analysis

Temperature, moisture content and the radial length were written in non-dimensional form in order to simplify the numerical calculations. The dimensionless temperature (θ) is defined as:

$$\theta = \frac{T - T_o}{T_a - T_o} \tag{5.12}$$

where:

T = temperature of the chickpea at any time during cooking (°C),

T_a = temperature of water (°C), and

T_o = initial or center temperature (°C).

The moisture ratio MR expressed in Equation 4.18 can also be referred to as the dimensionless moisture concentration C as given below:

$$MR = C \tag{5.13}$$

The dimensionless radial length (Ψ) is defined as:

$$\psi = \frac{r}{R} \tag{5.14}$$

where:

r = radial position (m), and

R = radius of the chickpea (m).

The heat and mass transfer equations explained above, in non dimensional form can be expressed as:

$$\frac{\partial \theta}{\partial t} = \frac{\alpha}{R^2}\left(\frac{2}{\psi}\frac{\partial \theta}{\partial \psi} + \frac{\partial^2 \theta}{\partial \psi^2}\right) \tag{5.15}$$

$$\frac{\partial C}{\partial t} = \frac{D_m}{R^2}\left(\frac{2}{\psi}\frac{\partial C}{\partial \psi} + \frac{\partial^2 C}{\partial \psi^2}\right) \tag{5.16}$$

$$\theta(\psi,0) = 1; \tag{5.17}$$

$$C(\psi,0) = 1; \tag{5.18}$$

$$\left.\frac{\partial \theta}{\partial \psi}\right|_{\psi=0} = 0; \tag{5.19}$$

$$\left.\frac{\partial C}{\partial \psi}\right|_{\psi=0} = 0; \tag{5.20}$$

$$\frac{k\partial\theta_s(T_a - T_o)}{R\partial\psi} = h(T_a - T_s) \tag{5.21}$$

$C_s = 1$ at $t>0$ for boiling

where:

C_s = concentration at the surface of the chickpea, and

t = time, s.

5.4 Solution Method

The solution method used to solve the finite difference equations is explained in this section. The equations are discretized to simplify the calculations and simulation.

5.4.1 Development of finite difference equations

A one-dimensional spherical finite difference framework, consisting of 10 concentric shells of equal thickness, was developed to model the heat and moisture concentration in a chickpea during cooking.

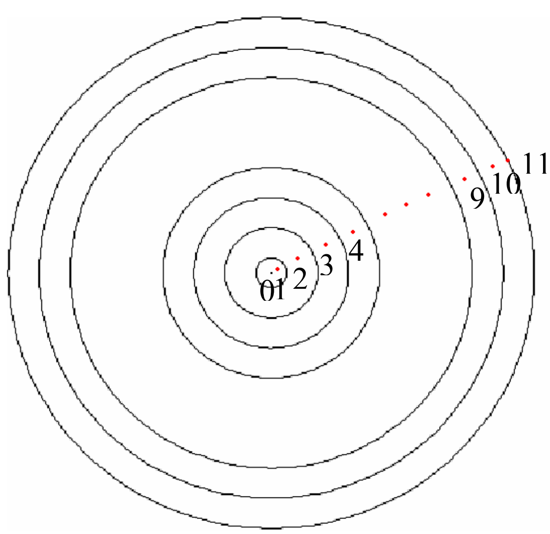

Figure 5.2 Position of nodes in the chickpea.

Eleven nodes in total, one at the center of each shell element and the 11th on the outer surface, were assigned. Temperature and moisture content at each of these nodes were assumed to be representative of the entire element. The position of the nodes taken is shown in Figure 5.2. The geometric center is represented by node 0 and the surface node by 11. All the other nodes are a representative of the entire element that has been divided from 1 to 10.

5.4.2 Discretization of the equations

In the finite difference approach, the problem domain is 'discretized' so that the dependent variables are considered to exist only at discrete points. The difference representation given in the following equations were automatically solved by the software. Only one unknown appears in the difference equation in a manner that permits evaluation in terms of known quantities. Derivatives are approximated by differences resulting in an algebraic representation of the partial differential equation.

Node 0 (Geometric center)

Using the boundary condition and the central difference:

$$\frac{d\theta_0}{dt} = 300\frac{\alpha}{R^2}(\theta_1 - \theta_0) \tag{5.22}$$

$$\frac{dC_0}{dt} = 300\frac{D_m}{R^2}(C_1 - C_0) \tag{5.23}$$

Nodes 1-9

Using the central difference

For temperature:

$$\left.\frac{d\theta_i}{dt}\right|_{i=1-9} = \frac{\alpha}{R^2}\left(\frac{2}{\psi_i}\frac{\theta_{i+1}-\theta_{i-1}}{2/10} + \frac{\theta_{i+1}-2\theta_i+\theta_{i-1}}{(1/10)^2}\right) \tag{5.24}$$

$$\frac{d\theta_1}{dt} = \frac{100\alpha}{R^2}(3\theta_2 - 2\theta_1) \tag{5.25}$$

$$\frac{d\theta_2}{dt} = \frac{100\alpha}{R^2}\left(\frac{5}{3}\theta_3 - 2\theta_2 + \frac{1}{3}\theta_1\right) \tag{5.26}$$

$$\frac{d\theta_3}{dt} = \frac{100\alpha}{R^2}\left(\frac{7}{5}\theta_4 - 2\theta_3 + \frac{3}{5}\theta_2\right) \tag{5.27}$$

$$\frac{d\theta_4}{dt} = \frac{100\alpha}{R^2}\left(\frac{9}{7}\theta_5 - 2\theta_4 + \frac{5}{7}\theta_3\right) \tag{5.28}$$

$$\frac{d\theta_5}{dt} = \frac{100\alpha}{R^2}\left(\frac{11}{9}\theta_6 - 2\theta_5 + \frac{7}{9}\theta_4\right) \tag{5.29}$$

$$\frac{d\theta_6}{dt} = \frac{100\alpha}{R^2}\left(\frac{13}{11}\theta_7 - 2\theta_6 + \frac{9}{11}\theta_5\right) \tag{5.30}$$

$$\frac{d\theta_7}{dt} = \frac{100\alpha}{R^2}\left(\frac{15}{13}\theta_8 - 2\theta_7 + \frac{11}{13}\theta_6\right) \tag{5.31}$$

$$\frac{d\theta_8}{dt} = \frac{100\alpha}{R^2}\left(\frac{17}{15}\theta_9 - 2\theta_8 + \frac{13}{15}\theta_7\right) \tag{5.32}$$

$$\frac{d\theta_9}{dt} = \frac{100\alpha}{R^2}\left(\frac{19}{17}\theta_{10} - 2\theta_9 + \frac{15}{17}\theta_8\right) \tag{5.33}$$

$$\left.\frac{d\theta_i}{dt}\right|_{i=2-9} = \frac{100\alpha}{R^2}\left(\frac{2i+1}{2i-1}\theta_{i+1} - 2\theta_i + \frac{2i-3}{2i-1}\theta_{i-1}\right) \tag{5.34}$$

Node 10 (near the surface), By both backward and central difference:

$$\frac{d\theta_{10}}{dt} = \frac{\alpha}{R^2}\left(\frac{2}{\psi_i}\frac{\theta_s-\theta_9}{\frac{1}{10}+\frac{1}{20}} + \frac{\frac{\theta_s-\theta_{10}}{1/20} - \frac{\theta_{10}-\theta_9}{1/10}}{\frac{\frac{1}{10}+\frac{1}{20}}{2}}\right) \tag{5.35}$$

$$\frac{d\theta_{10}}{dt} = \frac{400\alpha}{R^2}\left(\frac{40}{57}\theta_s - \theta_{10} + \frac{17}{57}\theta_9\right) \tag{5.36}$$

For moisture concentration:

$$\left.\frac{dC_i}{dt}\right|_{i=1-9} = \frac{D_m}{R^2}\left(\frac{2}{\psi_i}\frac{C_{i+1} - C_{i-1}}{2/10} + \frac{C_{i+1} - 2C_i + C_{i-1}}{(1/10)^2}\right) \tag{5.37}$$

$$\frac{dC_1}{dt} = \frac{100\alpha}{R^2}(3C_2 - 2C_1) \tag{5.38}$$

$$\frac{dC_2}{dt} = \frac{100D_m}{R^2}\left(\frac{5}{3}C_3 - 2C_2 + \frac{1}{3}C_1\right) \tag{5.39}$$

$$\frac{dC_3}{dt} = \frac{100D_m}{R^2}\left(\frac{7}{5}C_4 - 2C_3 + \frac{3}{5}C_2\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{5.40}$$

$$\left.\frac{dC_i}{dt}\right|_{i=2-9} = \frac{100D_m}{R^2}\left(\frac{2i+1}{2i-1}C_{i+1} - 2C_i + \frac{2i-3}{2i-1}C_{i-1}\right) \tag{5.41}$$

Node 10 (near the surface)

$$\frac{dC_{10}}{dt} = \frac{400\alpha}{R^2}\left(\frac{40}{57}C_s - C_{10} + \frac{17}{57}C_9\right) \tag{5.42}$$

Node 11(surface)

By backward difference:

The heat transfer equation for the surface node of zero volume can be formulated using the boundary conditions as follows:

$$k\left.\frac{\partial\theta}{\partial r}\right|_{r=R} = h(\theta_a - \theta_s) \tag{5.43}$$

$$\left.\frac{\partial\theta}{\partial r}\right|_{r=R} = \frac{h}{k}(\theta_a - \theta_s) \tag{5.44}$$

$$\frac{\theta_s - \theta_{10}}{\Delta r/2} = \frac{h}{k}(\theta_a - \theta_s) \tag{5.45}$$

Thus, for surface node:

$$\theta_s = \frac{\left(\frac{\Delta r}{2}\frac{h}{k}\theta_a + \theta_{10}\right)}{\left(1 + \frac{\Delta r}{2}\frac{h}{k}\right)} \tag{5.46}$$

5.5 Properties Used in Model Calculations

Constant properties namely, the heat transfer coefficient and mass transfer coefficient that involved in the heat and mass transfer modeling is discussed in this section.

5.5.1 Surface heat transfer coefficient (h_t)

The heat transfer coefficient is the property of convective heat transfer systems involving a solid surface and a fluid. It is one of the most important parameters necessary to design and control of food processing equipment where fluids (air, nitrogen, steam, water or oil), used as heating, cooling, frying, or cooking media. The surface heat convection coefficient depends on the thermo-physical properties of fluid and solid (density, specific heat, thermal conductivity). Convection is the most common means of heat transfer used for heating solid food stuffs.

5.5.2 Calculation of convective heat transfer coefficient

For the calculation of the convective heat transfer coefficient, the lumped body model was used. Aluminum balls of 9.51mm diameter were made to the size of chickpea were used to calculate the surface convection coefficient. The thermal conductivity of aluminum ranges from 230 to 240 W/mK.

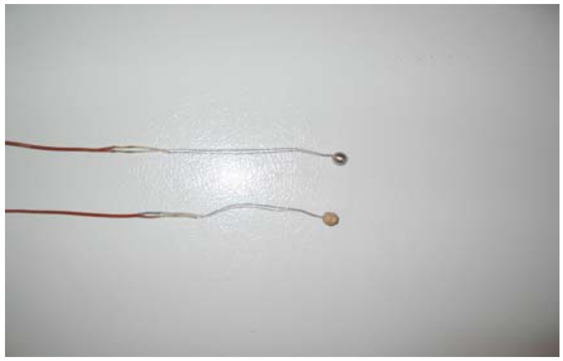

Figure 5.3 Aluminum sphere and chickpea seed during measurement of heat transfer coefficient.

Holes were bored to the center of the aluminum balls. A thermocouple wire was inserted and sealed with epoxy glue. This was placed in boiling water and the time-temperature data was collected. The temperature of the surrounding fluid was maintained constant throughout the process. This approximation can be made when the following condition in Equation 5.47 is satisfied (Incropera and DeWitt, 1996):

$$B_i = \frac{hL}{k} \leq 0.1 \tag{5.47}$$

where:

B_i = Dimensionless parameter Biot number,

h = convective heat transfer coefficient (W/m^{2}K),

k = thermal conductivity of aluminum (W/mK), and

L = r/3 for a sphere (m).

For a lumped body, the temperature of the solid which is introduced into the fluid at time t = 0 is given by:

$$\frac{T(t) - T_\infty}{T_i - T_\infty} = \exp\left(-\frac{hA}{mc_p}t\right) \tag{5.48}$$

where:

T_i = initial temperature of the aluminum sphere (K),

T_∞ = initial temperature of the aluminum sphere (K),

$T(t)$ = temperature at any time t (K),

A = surface area of the solid (m^2),

c_p = specific heat of aluminum (J/kgK),

m = mass of aluminum sphere (kg),

h = heat transfer coefficient (W/m^2K), and

t = time (s).

5.5.3 Diffusion coefficient (D_m)

Diffusion coefficient is the factor of proportionality representing the amount of substance diffusing across a unit area through a unit concentration gradient in unit time. Estimates of diffusion coefficient were obtained from experimental data using the sorption method with constant diffusion coefficient as outlined by Crank (1975). The moisture diffusion coefficient was calculated from Equation 4.17. This method is based on the assumption that the concentration at the surface of material when placed in a humid environment reaches equilibrium and remains constant thereafter (Fasina et al., 1993). For further calculations and modeling, the constant D_m value was used.

6. RESULTS AND DISCUSSION

This section of the thesis presents the experimental results obtained and the discussions of the results. The experimental results are compared with the simulated results.

6.1 Moisture Content

The moisture content of the whole grain chickpea samples selected randomly was adjusted to seven levels by drying, rewetting, soaking and cooking. The chickpea moisture content data are listed in Table 6.1 together with the mean, standard deviation and the coefficient of variation. The moisture content values obtained in replicates are shown in Table F1.

Table 6.1 Moisture content of chickpea seed samples used in experiments.

Level	Moisture content		
	Mean (% w.b.)	*SD (% w.b.)	**CV (%)
1	9.86	0.15	1.55
2	13.20	0.26	1.98
3	18.17	0.02	0.13
4	26.54	0.05	0.22
5	37.89	0.13	0.35
6	55.97	0.33	0.60
7	65.24	0.31	0.48

* Standard Deviation (n = 3)
** Coefficient of Variation

The standard deviation values ranged from 0.02 to 0.33% w.b. and the coefficient of variation was found to be between 0.13 to 1.98%, which shows the accuracy of the results obtained from the moisture content determination experiment.

6.2 Density

The particle density of the chickpea was measured using the gas pycnometer. Table 6.2 shows the results that were obtained. Table F2 shows the density values that were obtained during each trial. Before measuring the volume, the samples were sealed in airtight glass containers. Loss of moisture during the experiment must be taken into consideration. The samples when removed from the containers were transferred to the pycnometer cell immediately. The actual weight of the sample was less than the weight indicated when it was weighed. This may be due to the successive volume determinations yielding results trending in one direction where contaminants are removed after each depressurization. To reduce error, measurements were continued for five determinations for each level of moisture content. The pressure transducer used in this pycnometer dissipates a very slight amount of heat. Because of its extreme sensitivity, it can track a slight pressure increase associated with the heating of the gas. Accordingly, it is necessary to take the first reading observed after the digital display stabilizes. A change of approximately 0.001 on the digital display every 10-20 s is indicative of pressure increase due to heat dissipation and is normal. The most accurate and rapid results will be achieved by taking the first reading after the display stabilizes and then rotating the selector valve again and again immediately obtaining the first stable reading (Operating Manual, Quantachrome Corporation, 1900 Corporate Drive, Boyton Beach, FL 33426).

It was observed from the results that there was a decrease in the density of the chickpea for increased moisture contents. The kernel density of rewetted chickpea seeds were reported by Konak and co-workers (2002) for moisture content ranging from 5.2 to 16.5% d.b., the kernel density decreased from 1428 to 1368 kg/m^3 respectively.

Table 6.2 Particle density of chickpea as a function of moisture content.

Moisture content	Density		
(% w.b.)	Mean (kg/m^3)	SD (kg/m^3)	CV (%)
9.86	1459.44	19.07	1.31
13.20	1395.06	21.63	1.55
18.17	1384.18	21.05	1.52
25.10	1345.20	11.04	0.82
35.89	1305.51	9.19	0.70
55.97	1202.11	10.21	0.85
65.24	1109.82	3.36	0.30

n = 5

Dutta et al. (1988a) reported in their studies for moisture range from 9.64 to 31.0% d.b. that the kernel density of rewetted chickpea ranged from 1311 to 1257 kg/m^3. The same kind of trend was observed in the density values obtained in this experiment. As the initial moisture content was increased from 9.86 to 65.24% w.b., the density values decreased from 1459.44 to 1109.82 kg/m^3. Figure 6.1 shows the plot for particle density and seed moisture content.

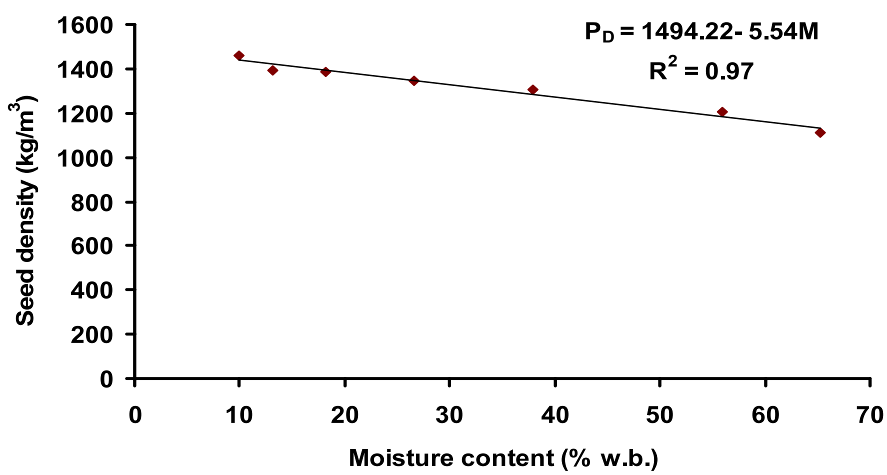

Figure 6.1 Seed density as a function of seed moisture content.

For moisture content of 65% w.b., the density was close to that of water. Equation

6.1 is the simple regression equation which was developed for particle density (P_D) as a function of moisture content:

$$P_D = 1494.22 - 5.54M \tag{6.1}$$

where:

M = moisture content (% w.b.).

The coefficient of determination (R^2) was found to be 0.97. The standard error of estimates was found to be 351.87 and the mean absolute deviation was found to be 17.04. The standard deviation ranged from 3.36 to 21.63 kg/m^3 and the coefficient of variation ranged from 0.30 to 1.55% which show the accuracy of the results obtained.

6.3 Thermal Conductivity

The thermal conductivity of chickpea was determined using the assembled probe. Thermal conductivity of distilled water was measured to calibrate the probe. Data was collected at 0.25 s intervals for over 40 to 50 s. Figure 6.2 shows a typical temperature history curve for distilled water at 25ºC. It was observed that there was a rapid rise in temperature at the beginning and the curve levelled off to a plateau after a certain period of time. The maximum slope was used to calculate the thermal conductivity. The k values ranged from 0.5641 to 0.5967 W/mºC. The thermal conductivity of water at 25ºC is approximately 0.6054 kJ/kg ºK (Beaton and Hewitt, 1989). Data for thermal conductivity measurement of chickpea was collected at 0.25 s intervals for over 100 s. Heating was rapid for the first 20 seconds as shown in Figure 6.3. The rate of rise in temperature became constant. The thermal conductivity of chickpea increased with increasing moisture content because of high thermal conductivity of water, ≈ 0.60 W/m°C.

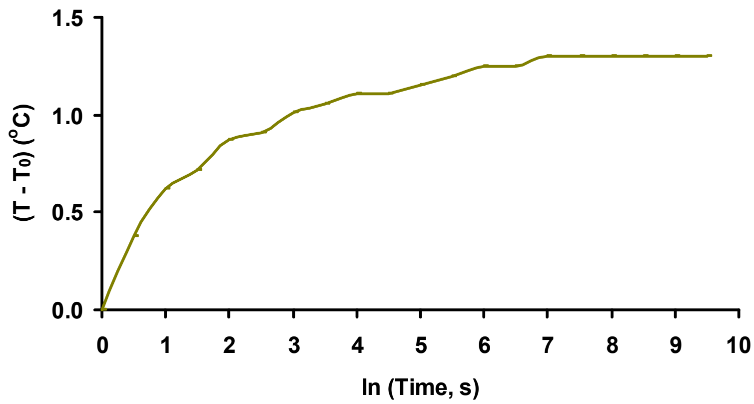

Figure 6.2 Typical experimental temperature history of distilled water at an initial temperature of 25ºC; T = temperature at any time (ºC) and T_o = initial temperature (ºC).

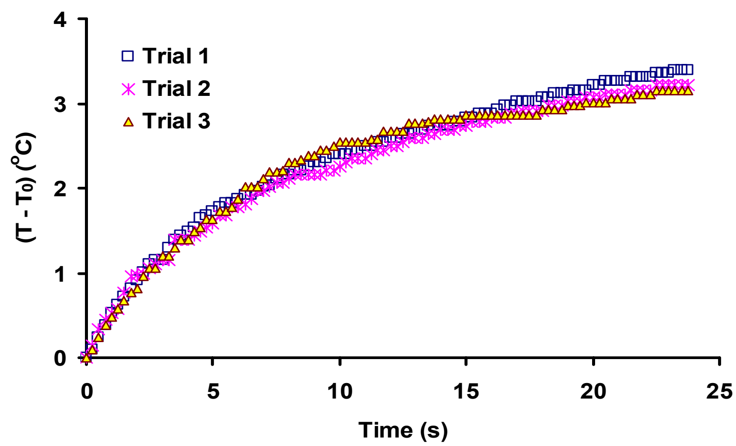

Figure 6.3 Typical temperature history curve for chickpea during measurement of thermal conductivity.

Table 6.3 shows the thermal conductivity mean values of kabuli chickpea at moisture content of 7.00 to 25.10% w.b., and temperature of 25 to 98°C. Table F3 gives the thermal conductivity values obtained during different trials. The slight deviations between the trials may be due to some axial flow errors and probe diameter errors which have been corrected to a maximum extent. It was observed that the thermal conductivity increased with increase in moisture content and temperature as shown in Fig 6.4. The values of thermal conductivity ranged from 0.1535 to 0.3257 W/m°C. The accuracy of the values was found by regression analysis. The standard deviation values obtained ranged from 0 to 0.0045 and the coefficient of variation ranged from 0.02 to 2.44%, which shows the accuracy of the results obtained. The thermal conductivity of borage seeds for moisture content ranging from 1.2 to 30.3% w.b., were reported to be 0.11 to 0.28 W/m°C by Yang and co-workers (2002).

Table 6.3 Determination of thermal conductivity using the assembled probe.

Temp (°C)	M.C (% w.b.)	K (W/m °C)		CV (%)	k model (W/m °C)
		Mean	SD		
25	7.00	0.1535	0.0006	0.39	0.1633
25	9.86	0.1849	0.0045	2.44	0.1795
25	13.20	0.2163	0.0009	0.42	0.1985
25	18.17	0.2365	0.0019	0.78	0.2268
25	25.10	0.2456	0.0011	0.48	0.2662
40	7.00	0.1694	0.0002	0.02	0.1757
40	9.86	0.1966	0.0020	1.04	0.1920
40	13.20	0.2294	0.0006	0.26	0.2110
40	18.17	0.2491	0.0009	0.39	0.2392
40	25.10	0.2637	0.0004	0.16	0.2787
60	7.00	0.1795	0.0005	0.30	0.1923
60	9.86	0.2029	0.0006	0.32	0.2086
60	13.20	0.2393	0.0009	0.38	0.2276
60	18.17	0.2632	0.0034	1.29	0.2558
60	25.10	0.2863	0.0007	0.26	0.2952
80	7.00	0.1886	0.0009	0.52	0.2089
80	9.86	0.2132	0.0012	0.59	0.2252
80	13.20	0.2529	0.0005	0.22	0.2442
80	18.17	0.2804	0.0007	0.25	0.2724
80	25.10	0.3001	0.0026	0.89	0.3118
98	7.00	0.2137	0.0023	1.11	0.2255
98	9.86	0.2343	0.0017	0.76	0.2417
98	13.20	0.2842	0.0016	0.58	0.2607
98	18.17	0.3091	0.0008	0.26	0.2890
98	25.10	0.3257	0.0004	0.15	0.3284

n = 3

The k values of borage seeds were slightly less than that of the thermal conductivity values of chickpea seed. The value of thermal conductivity increased with increasing temperature and moisture content. The magnitude and trend of the thermal conductivity of chickpea samples versus increasing moisture content were in agreement with the literature.

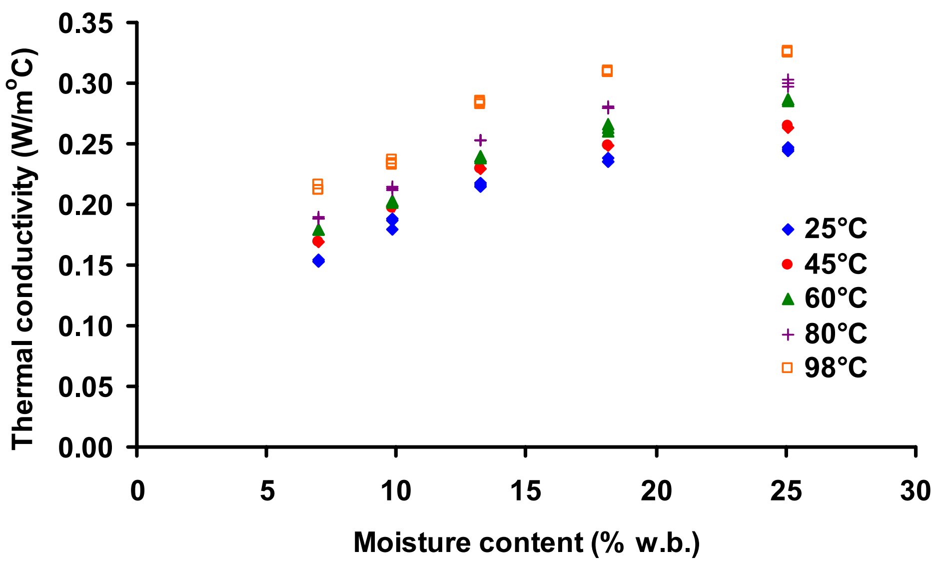

Figure 6.4 Thermal conductivity of chickpea as a function of moisture content and temperature.

Deshpande and co-workers (1996) observed a linear increase in bulk thermal conductivity of soybean from 0.1157 to 0.1756 W/m°C at 27°C in the moisture content range between 8 and 25% d.b. Shepherd and Bhardwaj (1986) reported that the bulk thermal conductivity of pigeon pea linearly increased from 0.1358 to 0.1862 W/m°C in the moisture content range of 8 to 26% d.b., and temperature range 10 and 40°C. The thermal conductivity of chickpea seeds was comparable with that of whole rapeseed

(0.108 to 0.155 W/m°C) at moisture contents from 6.1 to 12.8% w.b. and temperature 4.4 to 31.7°C (Mohsenin, 1980). The thermal conductivity values of alfalfa cubes were higher than chickpea and ranges from 0.31 to 0.48 W/mK at 4.8 to 57°C (Khoshtaghaza et al., 1995). The thermal conductivity value of chickpea seeds were higher than those of whole peanut kernels (Suter et al., 1975) and whole soybean seeds (Mohsenin, 1980), respectively.

The coefficient of determination R^2 for Equation 6.2 expressing the dependence of thermal conductivity to temperature and moisture content was 0.91 and a very small standard error of 0.0125, which shows the accuracy of the values. The variables moisture content, M (% w.b.) and temperature, T (°C) were analyzed with multiple linear regression using MS Excel (Microsoft Corporation, Redmond, WA).

$$k = 0.1027 + 0.0008T + 0.0056M \qquad (6.2)$$

The thermal conductivity was also determined using the KD2 thermal properties analyzer. The k of water determined was in a range of 0.55 to 0.60 W/m°C which was within the range given for water (Beaton and Hewitt, 1989). Chickpea seeds were inserted into the probe after drilling it to almost an equal diameter of the probe. The readings were taken for room temperature and the values of thermal conductivity were found to range from 0.16 to 0.32 W/m°C for moisture contents of 7.00 to 25.10% w.b.

6.4 Specific Heat

Specific heat results were obtained by two methods namely, the assembled calorimeter method and the DSC. In this section, the results obtained from both methods are discussed.

6.4.1 Assembled calorimeter method

The heat capacity of the assembled calorimeter was determined using equation 4.15 and was found to be 0.4568 kJ/kg°C. Figure 6.5 shows the time-temperature curve obtained during measurement of heat capacity of the calorimeter. Appendix F, Table F4 shows the heat capacity of the assembled calorimeter during calibrations.

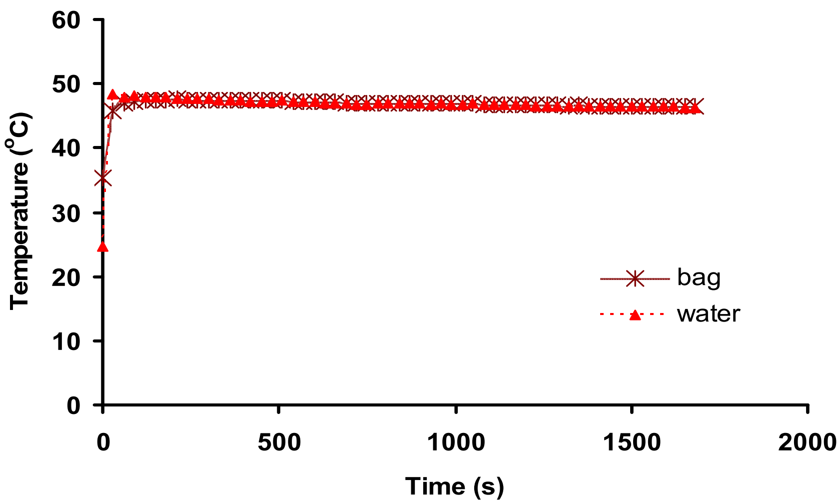

Figure 6.5 Time-temperature data during heat capacity measurement of calorimeter.

The average heat capacity value obtained was used to do further calculations in finding the specific heat of chickpea. Accuracy of the heat capacity values can be noted from the very small standard deviation of 0.0034 and the equally low coefficient of variation of 0.75%. The specific heat values of chickpea at seven different moisture levels are shown in Table 6.4. The specific heat values of chickpea obtained during different trials are shown in Table F5. The specific heat values obtained was found to be between 1.3749 to 2.4802 kJ/kg°C as the moisture content increased from 9.86 to 65.24%. The standard deviation ranged from 0 to 0.05 and the coefficient of variation ranged from 0.49 to 2.35% which shows the accuracy of the results. Figure 6.6 shows a typical time-temperature curve obtained from the experiment conducted for the sample.

Table 6.4 Specific heat values for chickpea by assembled calorimeter method.

Moisture content (%)	Specific heat Mean (kJ/kg°C)	SD (kJ/kg°C)	CV (%)	c_p model (kJ/ kg°C)
9.86	1.375	0.01	1.17	1.578
13.20	1.582	0.01	0.85	1.635
18.17	1.849	0.00	0.49	1.718
25.10	1.966	0.02	1.14	1.835
35.89	2.135	0.05	2.35	2.017
55.97	2.264	0.03	1.76	2.355
65.24	2.480	0.01	0.59	2.512

n = 3

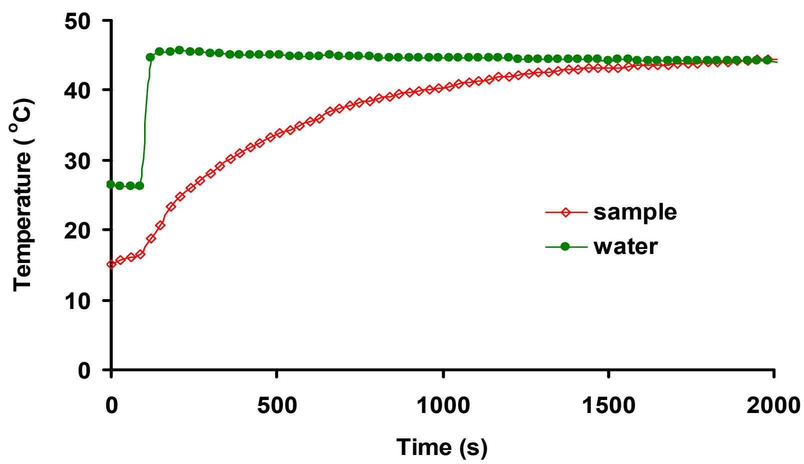

Figure 6.6 Typical time-temperature curve for specific heat measurement of sample using assembled calorimeter method.

Young and Whitaker (1973) demonstrated that specific heat increased as the temperature increased. Result obtained by Suter and co-workers (1975) indicated that within the range of variables studied, an increase in temperature caused an increase in specific heat of peanut pods. The specific heat of locust bean seed was found to be 1.6946 and 1.1307 kJ/kgK which is slightly less that the values obtained for chickpea (Ogunjimi et al., 2002).

Based on the experimental data, the specific heat of kabuli type chickpea was expressed in the form of a simple regression equation as a function of moisture content which is shown in Equation 6.3.

$$c_p = 1.412 + 1.685M \qquad (6.3)$$

where:

c_p = specific heat (kJ/kg°C), and

M = moisture content (% w.b.).

The coefficient of determination (R^2) of Equation 6.3 was found to be 0.86. The major source of error that can occur in this method is the heat lost from the calorimeter to the surroundings. The flasks were well insulated and there was minimal loss of heat to the surroundings.

6.4.2 DSC method

Specific heat results obtained by the differential scanning calorimeter are shown in Figure 6.7. The graphs obtained are shown in Appendix A. It was determined for six levels of moisture content with temperatures ranging from 30 to 80°C. Due to the limited access to the instrument, only one replicate of results were obtained for different moisture contents. The specific heat values obtained from the DSC is shown in Figure 6.8 and the values are expressed in the form of a table in Table F6. At increased moisture content and temperature, a uniform rise in the specific heat values, was observed. It can be observed from Figure 6.7 that the specific heat increased linearly with increase in the temperature for different moisture contents. The specific heat of distilled water using the DSC was reported by Tang et al. (1991) to be within the range of 4.13 to 4.19 kJ/kgK for temperature ranging between 10 to 80°C. The specific heat of kabuli chickpea obtained from the DSC measurement ranged from 1.377 to 2.577 kJ/kgK.

Specific heat values obtained using DSC for laird lentil seeds for moisture contents ranging from 2.1 to 25.8% w.b., and temperatures of 10 to 80°C were reported to be 0.81 to 2.2 kJ/kgK (Tang et al., 1991). These values were lower than that of kabuli chickpea seeds in this experiment. Heat capacity of fuzzy and starch coated cotton seeds was reported to be between 1.20 and 2.95 kJ/kgK and between 1.31 and 3.16 kJ/kgK, respectively (Turhan and Gunasekaran, 1999). It was also reported that the heat capacity increased linearly with moisture content. The heat capacity of soybean linearly increased from 1.91 to 2.91 kJ/kgK at 27°C with moisture content ranging from 8.1 to 25% d.b., (Deshpande et al., 1996). The specific heat value of borage seeds found using DSC method ranged from 0.77 to 1.99 kJ/kgK (Yang et al., 2002). Dutta et al. (1988b), Mohsenin (1980), and Murata et al. (1987) reported that specific heat increased linearly with moisture content. The same kind of trend was not observed in the results obtained for chickpea.

In general, specific heat increased with temperature almost linearly as shown in the Figure 6.7. A simple regression equation was developed as a function of moisture and temperature with the specific heat values obtained from the DSC method. The R^2 value for Equation 6.4 is 0.97.

$$c_p = 1.060 + 0.017M + 0.004T \tag{6.4}$$

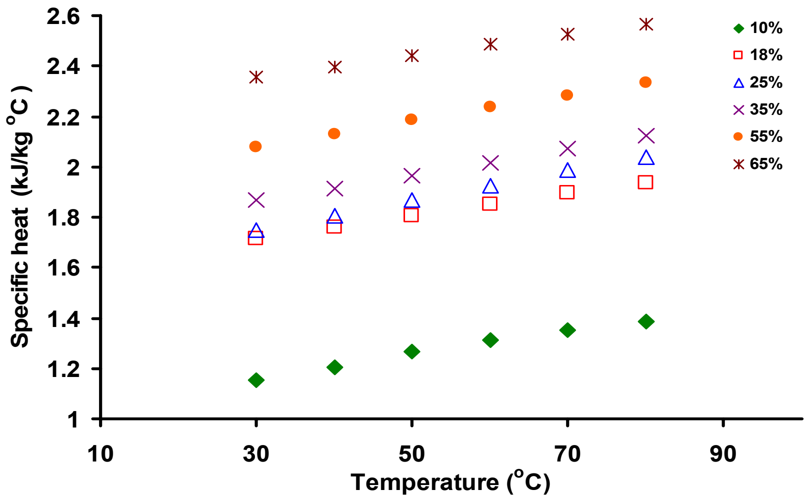

Figure 6.7 Specific heat values obtained from the DSC

The DSC is a comparative device and must be calibrated. In this experiment, it was done using sapphire. Tang et al. (1991) reported that due to low thermal diffusivity of biological materials, thermal lag within the sample may introduce error in the measured values of specific heat. Although samples containing high moisture content were used in this experiment, the pans were perfectly sealed to prevent evaporation. A correlation between the specific heat values obtained by both methods could not be made because the values obtained by the assembled calorimeter was obtained by varying the moisture content only whereas the values obtained by the DSC were a function of both temperature and moisture contents.

6.5 Thermal Diffusivity

Thermal diffusivity was determined using the calculated specific heat and thermal conductivity values. The thermal diffusivity values were calculated with the values obtained by the assembled calorimeter and the DSC separately. Figure 6.8 shows the diffusivity values obtained from specific heat values using the assembled calorimeter method. Each value is a mean of three replicates. The thermal diffusivity values obtained from calculations of the values obtained from specific heat values using the assembled calorimeter experiment ranged from 9.21×10^{-8} to 2.51×10^{-7} m^2/s. The accuracy of the results can be noted from a very small standard deviation values ranging from 1.07×10^{-9} to 3.85×10^{-9} and the coefficient of variation was also low with values from 0.59 to 2.38%.

The magnitude of thermal diffusivity, α, depends on the combined effects of k, ρ and c_p according to Equation 4.16. For grain, where the value of thermal conductivity increases faster than that for ρ and c_p at the same temperature and moisture ranges, the thermal diffusivity increases with moisture content. The contribution of k value is at a larger magnitude than c_p. The thermal diffusivity values obtained are expressed in the form of a table in Table F7.

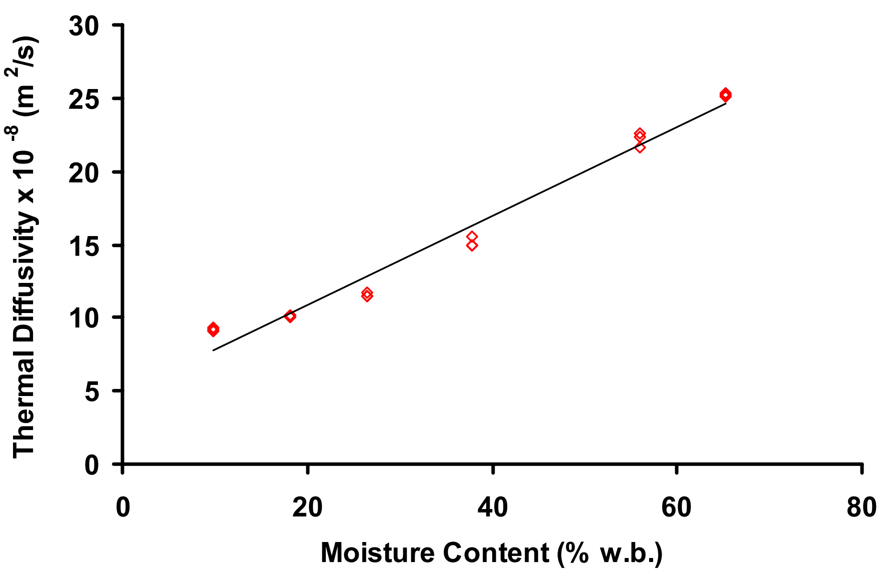

Figure 6.8 Thermal diffusivity values obtained by the assembled calorimeter method.

The variation of thermal diffusivity values of chickpea seeds at six different moisture content levels measured at temperatures ranging from 30 to 80°C are shown in Figure 6.9. It can be observed that thermal diffusivity values increased with an increase in moisture content, but decreased with increase in temperature from 30 to 80°C. Computed values of the thermal diffusivity were sensitive to temperature rise and were found to decrease as the temperature increased. A simple regression equation was developed as a function of moisture, M(% w.b.) and temperature, T(°C) with the thermal diffusivity values obtained. The R^2 value for Equation 6.5 is 0.97.

$$\alpha = 13.0898 \times 10^{-8} - 0.0908 \times 10^{-8} T + 0.2038 \times 10^{-8} M \qquad (6.5)$$

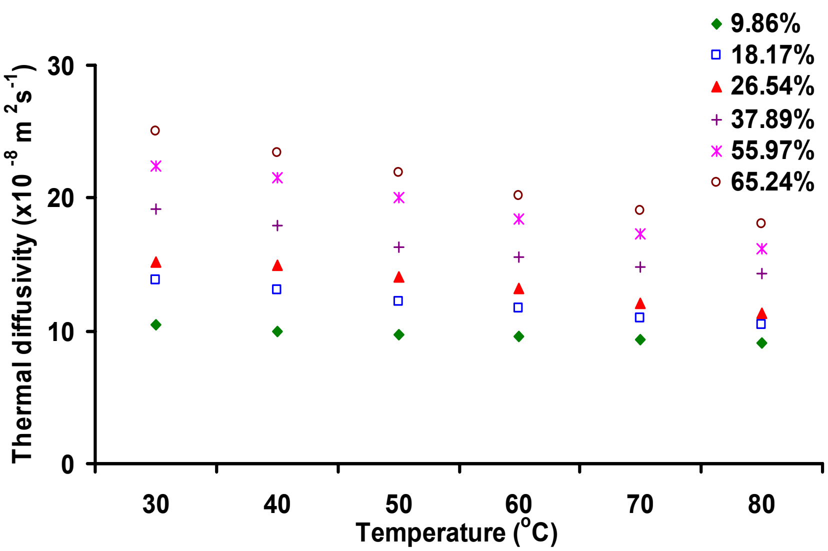

Figure 6.9 Thermal diffusivity values obtained by the DSC method.

Thermal diffusivity of soybean linearly increased from 2.9×10^{-4} to 3.1×10^{-4} m^2/s at 27°C in the moisture content range of 8.1 to 25% d.b. (Deshpande et al., 1996). The thermal diffusivity of pistachio decreased linearly from 4.8×10^{-8} to 3.2×10^{-8} m^2/s at room temperature in the moisture content range of 8 to 65% d.b. (Hsu et al., 1991). Diffusivity of peanut specimens decreases with temperature increase, being the lowest for whole peanuts and highest for ground kernels (Suter et al., 1975). Borage seeds had thermal diffusivity values ranging from 2.32×10^{-7} to 3.18×10^{-7} m^2/s (Yang et al., 2002). The thermal diffusivity of meatballs was 1.6×10^{-7} m^2/s during boiling (Huang and Mittal, 1995). The thermal diffusivity of alfalfa cube decreased linearly from 3.99×10^{-7} to 2.55×10^{-7} m^2/s as the initial cube temperature increased from 4.7 to 57°C (Khoshtaghaza et al., 1995). A similar trend was observed in the thermal diffusivity values of chickpea seed.

6.6 Moisture Absorption of Chickpea

The moisture absorption results obtained during soaking at four different levels of temperature are shown in Figure 6.10. Each value represents a mean of three values. The temperatures mentioned in this experiment refer to the temperature of the chamber where water was placed in a beaker. In this study, the diameter of the chickpea samples were intentionally kept between 9-10 mm and their initial moisture content at 10.93% d.b.

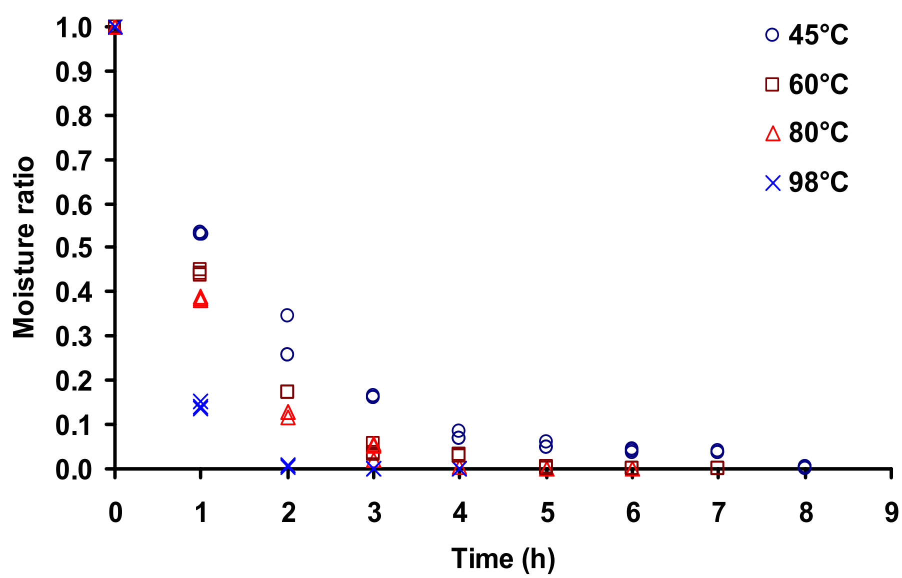

Figure 6.10 Moisture absorption of chickpea during soaking in water.

It can be observed from Figure 6.10 that at high water temperature, the moisture was absorbed at a faster rate compared to lower water temperatures. When soaked in water at 45°C, it took almost 9 hours for the seed to get fully soaked. It was observed that when the seed reached a moisture content of 55% w.b., at temperatures ranging from 45 to 98°C, it was fully soaked. This was the maximum amount of moisture that the seed could absorb during soaking. It is known that overnight soaking of chickpea at room temperature results in fully soaking the chickpea seed. Chickpea samples exhibited typical sorption behavior with increasing water content versus soaking time at all temperature with reference to Figure 6.10. As the process continued, water absorption rate decreased steadily due to water filling into the free capillary and intermicellar spaces, and increasing the extraction rates of soluble solids from grains (Abu-Ghannam and McKenna, 1997). As the driving force in the water movement decreases, the extraction of soluble solids in the reverse direction to the water movement offers additional resistance to water transfer (Sayar et al., 2001). Water absorption ceased when the grains attained the equilibrium water content. The rate of water absorption increased with increasing temperature as suggested by the slopes of the absorption curves getting steeper with increased temperature. The behavior of material during moisture absorption depends on the heat and mass transfer characteristics of the product (Fasina et al., 1993).

Earlier studies reported that the water absorption rate by whole beans is influenced by seed size (Hung et al., 1993), initial water content (Smith and Nash, 1961), and thickness and structure of seed coat (Abu-Ghannam and McKenna, 1997; Singh and Kulsherstha, 1987). A shorter soaking step not only means less processing time but also signifies retention of more soluble solids in the seeds.

The gelatinization temperature of chickpea starts between 55 to 60°C. Sayar and co-workers (2001) and Fernandez and Berry (1989) reported that gelatinization temperature ranged between 63 to 70°C for chickpea where the temperature range is fairly close. The gelatinization temperature was around 75°C for whole wheat (Turhan and Gunasekaran, 2001), 80°C for whole corn (Cabrera et al., 1984), 85°C for whole rice (Bakshi and Singh, 1980; Birch and Priestly, 1973) and 60°C for whole soybean (Kubota, 1979).

It was also reported that the rate of water absorption by legumes increased with increase in the temperature of the soaking water (Quast and de Silva, 1977; Tang et al., 1994; Sopade and Obekpa, 1990; Abu-ghannam and McKenna, 1997; Hung et al., 1993 and Hsu et al., 1983).

6.7 Cooking Time of Chickpea

This experiment was done to predict the cooking time of both soaked and unsoaked chickpea seeds and also to measure the center temperature of the chickpea seed. The increase in moisture content of the chickpea during cooking was also found. Unsoaked chickpea had an initial moisture content of 9.86% w.b., and the moisture content of the soaked chickpea was 55% w.b. Soaked seeds were obtained by fully soaking them for 12 h in water at room temperature. Table 6.5 shows the change in seed moisture content during cooking of chickpea at three different temperatures. Figure 6.11 shows the time taken to cook the seed, and its corresponding moisture content and temperature.

Table 6.5 Moisture content (% w.b.) of chickpea as a function of temperature and cooking time.

Cooking time (min)	Cooking temperature (°C)		
	80(°C)	90(°C)	98(°C)
0	55.44[+]	55.51	55.94
15	57.92	59.01	59.90
30	58.74	59.92	61.04
45	60.23	61.17	62.24
60	61.24	62.15	
90	62.23	62.45	
140	63.41	63.84	
270	64.76		
300	65.00		

n = 3

[+] Moisture content of cooked chickpea (% w.b.)

This experiment was also conducted at lower water temperatures like 70°C, but the seeds were uncooked although the temperature was in between the gelatinization temperature range. It was observed that the chickpea cooked only at higher temperatures equal to or higher than 80°C. From Table 6.5, it can be noted that at a temperature of 98°C the seed cooked in 45 min. For cooking temperature of 90°C, it took around 140 min for the seeds to get cooked. The seed was firmly pressed between the fingers to see if it was cooked. It was observed that only at higher temperatures, the starch gelatinized and the seed was cooked. The seed was found to be cooked when it reached moisture content of 62% w.b., at a constant water temperature of 98°C; a seed was cooked when its moisture content was 65% w.b., at a constant water temperature of 80°C. The maximum moisture that could be reached by traditional cooking with the cover open was 65% w.b. Figure 6.11 shows the time taken for the soaked and unsoaked chickpea to get cooked. This experiment was repeated for three replicates and each point on the graph (Figure 6.11) is the mean of three values.

Conventional cooking time was found to be 110 min for chickpea and 55 min for common beans (Marconi et al, 2000). Tarek (2002) reported a cooking time of 90 min for chickpea seeds when cooked at a constant water temperature of 100°C, and he also reported that the cooking process was terminated when the seeds were soft when felt between the fingers.

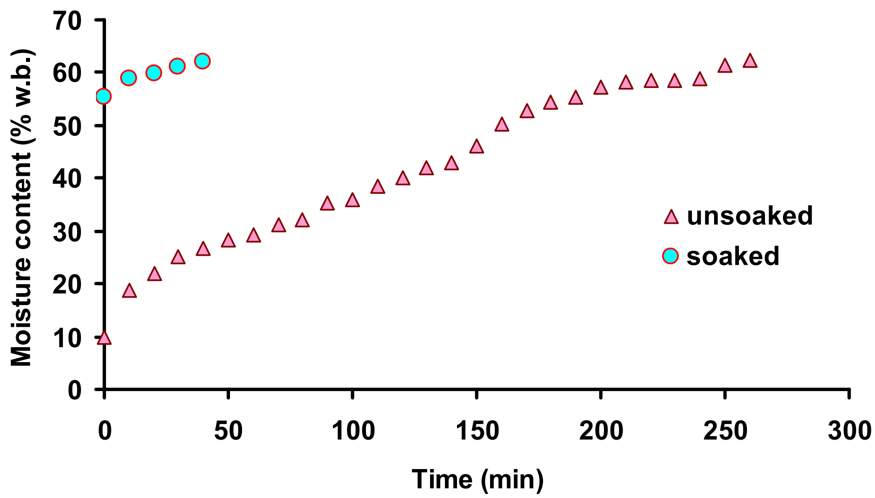

Figure 6.11 Cooking of soaked and unsoaked chickpea at 98°C.

This experiment was conducted only for temperature of 98°C. It can be noted from Figure 6.11 that it took about 45 min to cook the soaked chickpea seeds, whereas it took approximately 250 to 300 min to cook the unsoaked chickpea. Reyes-Moreno and co-workers (2001) reported that cooking time of whole grains of fresh chickpea varied from 112 to 142 min. This cooking time is higher than the values obtained in this experiment. Reyes-Moreno and Paredes-Lopez (1994) also reported that the cooking time of common beans was between 59 to 90 min. This cooking time was fairly close to the cooking time of the soaked chickpea found in this experiment.

6.7.1 Temperature of the center of chickpea during cooking

The temperature distribution was recorded for temperatures ranging from 70 to 98.7°C for both soaked and unsoaked seeds. Each combination was done in two replicates where the temperature of the center of chickpea was measured.

When cooked at 70°C, the seeds which were either soaked or unsoaked did not get cooked to the edible stage. The gelatinization temperature was reported by Klamczynska et al. (2001) in the range of between 52 and 109°C. Figures 6.12 and 6.13 show the temperature curve of the center of chickpea while cooked at temperatures ranging from 70 to 98°C, for unsoaked and soaked seeds, respectively. The center temperature for Figures 6.12 and 6.13 are represented in the form of tables in Appendix E.

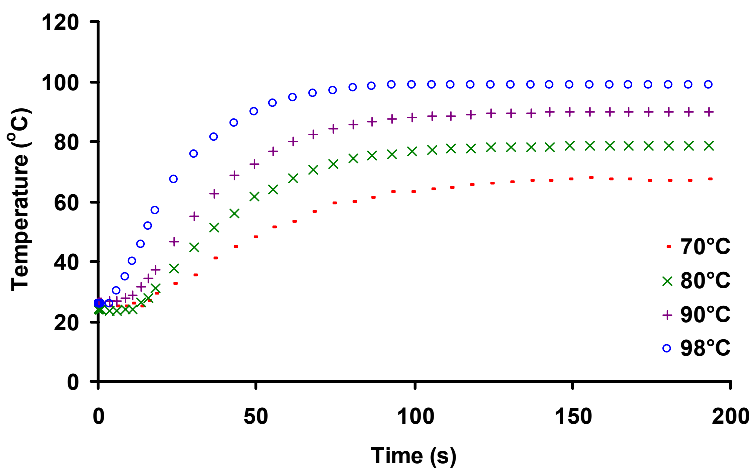

Figure 6.12 Center temperature of unsoaked chickpea during cooking at different temperatures.

It can be observed from the curve that the temperature increase is higher at higher temperatures than at lower temperatures. It can be observed from the experimental results that the chickpea seeds attained an equilibrium temperature at a faster rate when they were first soaked and then cooked at higher temperatures. This experiment was conducted to be compared with the simulated temperature distribution curve.

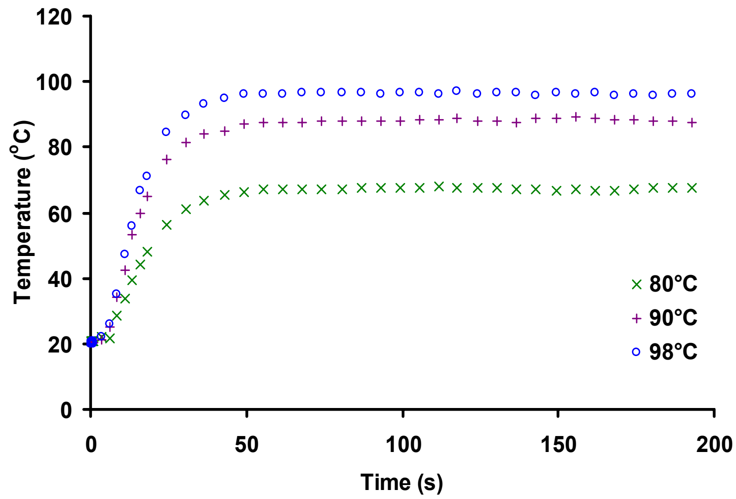

Figure 6.13 Center temperature of soaked chickpea during cooking at different temperatures

6.7.2 Moisture diffusivity

Diffusion coefficient values were calculated using Equation 4.17. The diffusion coefficient values obtained from the calculations ranged from 1.37×10^{-11} to 5.51×10^{-10} m^2/s as the temperature increased from 45 to 98.7°C, (Table 6.6). The diffusion coefficient listed in Table 6.6 is a mean of three values.

Table 6.6 Diffusion coefficient values.

Temperature (°C)	Diffusion Coefficient ($\times 10^{-10}$ m^2/s)
45.0	0.14
60.0	0.82
70.0	0.85
80.0	1.34
90.0	3.95
98.7	5.51

The magnitude of diffusion coefficient reported by (Sayar et al., 2001) for temperatures ranging from 20 to 100°C were 2.43 to 39.16×10^{-10} m^2/s for spring chickpea and 1.99 to 36.94×10^{-10} m^2/s for winter chickpea. Normally, the moisture diffusivity in a solid material increases with porosity and moisture content. The water diffusion coefficient of chickpea ranged from 9.71×10^{-11} to 5.98×10^{-10} m^2/s (Gúrtas et al., 2001). Diffusivity values reported in this study were quite similar to the published literature results for different grains such as soybean (2.15×10^{-11} m^2/s at room temperature) (Deshpande et al., 1994) and white rice (5.2×10^{-11} m^2/s at 30°C) (Engels et al., 1986). The diffusivity values used for simulation were taken from the experimental results.

6.8 Mass Loss

Table 6.7 shows the percentage of solid loss during soaking of chickpea at different temperatures. Table F8 shows the values obtained during replicates. It was observed that at higher soaking temperatures, the percentage solid loss was higher when compared to seeds soaked at low temperatures. The accuracy of the results obtained can be noted from the very small standard deviation values of between 0.05 to 0.18 and the coefficient of variation of between 0.94 to 4.06%. The percentage of solid loss was found to be between 1.95 to 6.24% for temperatures ranging from 25 to 100°C. It can be recommended from the results obtained, that it is safe to soak the chickpea at lower temperatures between 25 to 40°C to reduce the amount of soluble solids losses to less than 3%. Kon (1979) reported that losses of total solids, N-compounds, total sugars, oligosaccharides, Ca, Mg, and vitamins were very small at soaking temperature of up to 50°C, but increased three to four times at soaking temperature of 60°C or above.

Table 6.7 Determination of solids loss during soaking of chickpea.

Temperature (°C)	Solids loss		
	Mean (%)	SD (%)	CV (%)
100	6.24	0.05	0.94
80	5.28	0.18	3.51
60	3.96	0.13	3.51
40	2.61	0.10	4.06
25	1.95	0.06	3.42

n = 3

Gúrtas and Evranus (1992) reported that the loss of soluble solids from chickpea soaked at 40°C for 18 h to be around 1% of the original mass. Solid losses reported by (Marconi et al., 2000) during conventional cooking in water was found to be 10.6% in chickpea and 7.5% in common beans. Fasina and co-workers (1997) reported that leaching losses from processed (infrared heated) seeds after 24 h of soaking was 10-11% and that of unprocessed (raw) seeds which were ranged between 1 and 5%. For pinto beans, it took 30 min to 1 h to lose 4% of initial solids at temperatures of 80 and 100°C. The solid loss at 80°C was found to be as high as 10% and that the solid loss increased significantly with increase in soaking temperature (Pan, 2002). The temperature of the soaking medium was a major factor in reducing the soaking time in the processing of dry Turkish legumes.

6.9 Simulation Results

Simulation was done to predict the temperature distribution and moisture diffusion in the chickpea seed during cooking at different temperatures.

6.9.1 Transport properties used in modeling

The surface heat transfer coefficient values ranged from 212.26 to 351.08 W/m^2K calculated from Equation 5.48 for different temperatures using aluminum balls. It was observed that the heat transfer coefficient increased as the temperature of the cooking water increased from 70 to 98.7°C. Seeds selected for cooking were of size 9 to 10 mm in diameter. Surface area of the seed as reported by Dutta et al. (1988a) was 133.4 mm^2. The surface area of aluminum balls were 284 mm^2. The surface area of chickpea seed used in the experiment was around 290 mm^2. The diffusion coefficient values used for the simulation were obtained from Equation 4.17. The program that was used to simulate the temperature distribution and moisture diffusion is shown in Appendix B.

6.9.2 Simulated and experimental temperature and moisture histories

Results obtained from cooking are illustrated in the following sections. The simulated temperatures of the chickpea at different locations in the seed from the center to the surface during cooking at different temperatures are shown in Appendix C. Figures 6.14 and 6.15 show the closeness of the simulated and experimental data for the center temperature of chickpea subjected to conventional cooking at temperatures ranging from 70 to 98.7°C for both unsoaked and soaked chickpea seeds. The mean absolute deviation from simulated and experimental results for temperature distribution of soaked seed at temperatures ranging from 70 to 98.7°C ranged from 0.0110 to 0.300 and the standard error of estimates ranged from 0.2048 to 1.4369. For unsoaked chickpea, the mean absolute deviation obtained ranged from 0.0083 to 0.0337 and the standard error of estimates was found to range from 0.1094 to 1.7856, respectively.

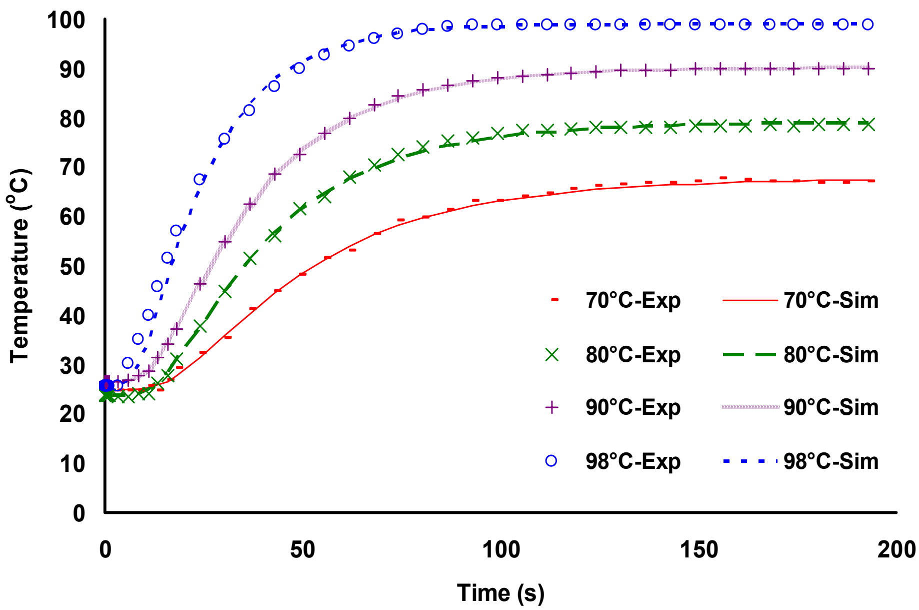

Figure 6.14 Experimental and simulated center temperature during cooking of unsoaked chickpea.

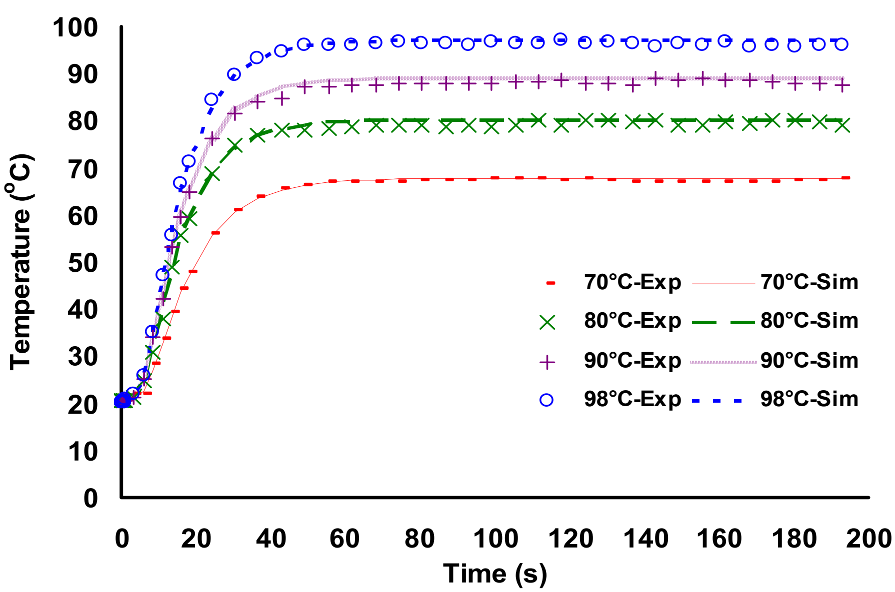

Figure 6.15 Experimental and simulated center temperature during cooking of soaked chickpea.

The deviations of the simulated and experimental values of seed temperature during cooking for both soaked and unsoaked chickpea seeds at different cooking temperatures are shown in Appendix D. The deviations were found to be between -4 to 4°C for soaked chickpea and -2 and 3°C for unsoaked chickpea. Very small deviations show the accuracy of the results obtained.

Simulated average moisture ratio and the moisture ratio obtained from experimental results as affected by different cooking temperatures are shown in Figures 6.16 and 6.17 for both unsoaked and soaked chickpea.

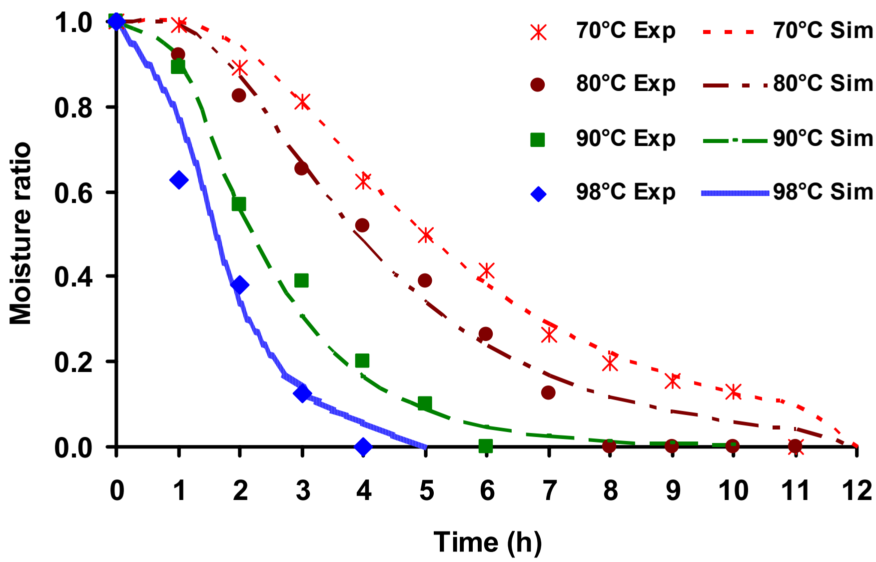

Figure 6.16 Experimental and simulated moisture ratio during cooking of unsoaked chickpea.

The results obtained from simulation are found to be fairly close to that of the experimental values. The mean absolute deviation for moisture ratio changes during cooking of soaked chickpea at temperatures ranging from 70 to 98.7°C were between 0.009 to 0.352 and the standard error of estimates were between 0.0005 to 0.0040. For unsoaked chickpea, the mean absolute deviation between experimental and simulated moisture ratio changes ranged from 0.0214 to 0.0445 and the standard error of estimates was found to range from 0.0011 to 0.0041.

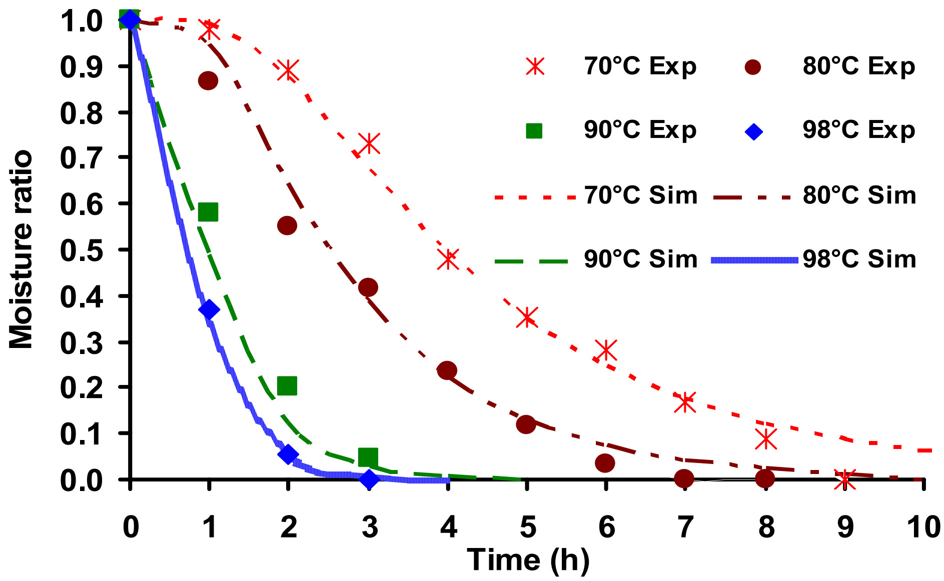

Figure 6.17 Experimental and simulated moisture ratio during cooking of soaked chickpea.

The deviation of moisture ratio between simulated and experimental results is shown in Appendix D. The deviations ranged from -0.15 to 0.15 for soaked and unsoaked chickpea. The simulated values when compared to the experimental values had small deviations which prove the accuracy of the results obtained.

7. SUMMARY AND CONCLUSION

This chapter deals with the conclusions based on results obtained from the experiment and the simulation of temperature and moisture distribution in the chickpea seed. The principal objective of this thesis was to model and simulate the moisture diffusion and temperature distribution during cooking of chickpea. The first specific objective of this thesis was to develop a heat and mass transfer equation during cooking of chickpea grain. Considering the chickpea grain to be spherical in geometry, one dimensional heat and mass transfer equations were developed. The finite difference method was used to solve the partial differential equations.

The second objective was to determine the thermo-physical properties in chickpea. Thermal conductivity as a function of moisture content and temperature was found to range between 0.1535 to 0.3257 W/m°C for moisture contents ranging from 7.00 to 25.10% w.b., and temperature of 25 to 98°C. The values obtained were fairly close to the values obtained from the previous literature for chickpea.

Specific heat values determined using the assembled calorimeter ranged from 1.3749 to 2.4802 kJ/kg°C as the moisture content increased from 9.86 to 65.24% w.b. The specific heat values obtained using the DSC was found to be a function of both temperature (30 to 80°C) and moisture content (6.86 to 65.24% w.b.) and the values ranged from 1.377 to 2.577 kJ/kg°C. The calculated thermal diffusivity values were found to be between 9.21×10^{-8} to $2.51\times10^{-7} m^2/s$.

The third objective was to experimentally determine the moisture absorption during soaking and cooking and also the temperature distribution during cooking.

Soaking time, the rate of moisture transfer and the maximum amount of moisture that the seed could absorb when soaked at different temperatures were determined. The moisture absorption results were also used to find the diffusion coefficient values which ranged from 1.37×10^{-11} to 5.51×10^{-10} m^2/s as the temperature increased from 45 to 98.7°C.

Cooking experiment resulted in experimentally finding the optimum cooking time of the chickpea when cooked at different temperatures. The rate of heat transfer was also found by experimentally determining the temperature distribution.

The properties found experimentally were used to simulate and predict the temperature and moisture distribution during cooking. It was observed that the simulated and experimental values when statistically tested for closeness were found to be fairly close.

Chickpea is known for its rich protein and starch content. Loss of soluble solids during cooking in chickpea is one of the major factors to be considered. The loss of soluble solids ranged from 2% to 6% as the soaking temperature increased from 45 to 98°C. Hence, the optimum soaking time at a temperature ranging from 25 to 40°C was found to be 8 h and cooking time at cooking temperature of 98.7°C was 45 to 50 min. These optimal conditions resulted in minimal solids losses in the seeds during conventional cooking.

8. RECOMMENDATIONS

The finite difference model developed in this study is expected to be useful for other biological materials. This study is restricted to traditional cooking and further investigation can be conducted on different heat treatment methods such as pressure cooking, microwave cooking, roasting and frying.

This thesis has been done to study the moisture transfer and temperature distribution during conventional cooking of chickpea. Future studies can be extended to consider other factors like internal physico-chemical changes and pressure distribution when subjected to processing at high temperatures. Chickpea is widely pressure cooked in retorts for canning hence a detailed study on pressure distribution is needed.

Simulation of results based on changes of thermal diffusivity (α), specific heat (c_p), thermal conductivity (k) and density (ρ), as functions of temperature and moisture content were not conducted. Future simulation studies which include the temperature and moisture dependence of the above thermo-physical properties could be of value in understanding the heat and mass transfer phenomena during chickpea cooking.

Exposure to prolonged periods of soaking or cooking resulted in loss of nutrients, mainly soluble solids in chickpea. Percentage of solid loss during soaking has been studied and further investigation can be conducted to analyze the soluble solids that are lost during cooking and to make this loss to a minimum. Investigations on the textural changes of the raw to cooked seed can be conducted to determine the time at which the cooking process can be terminated.

Optimizing the cooking process to minimize the amount of energy needed to cook and also to find the suitable method for cooking the seeds in water by comparing the results when cooked using different methods can also be considered.

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APPENDICES

APPENDIX A

Specific Heat Measurement by DSC

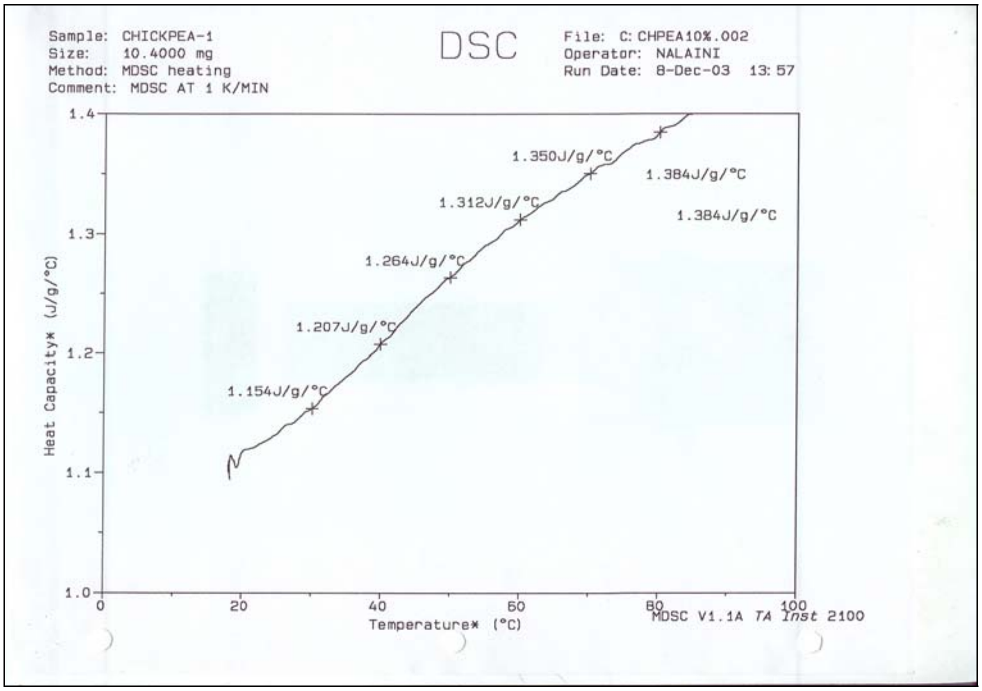

Figure A1. Specific heat values of chickpea seed sample at 9.86 % w.b moisture content.

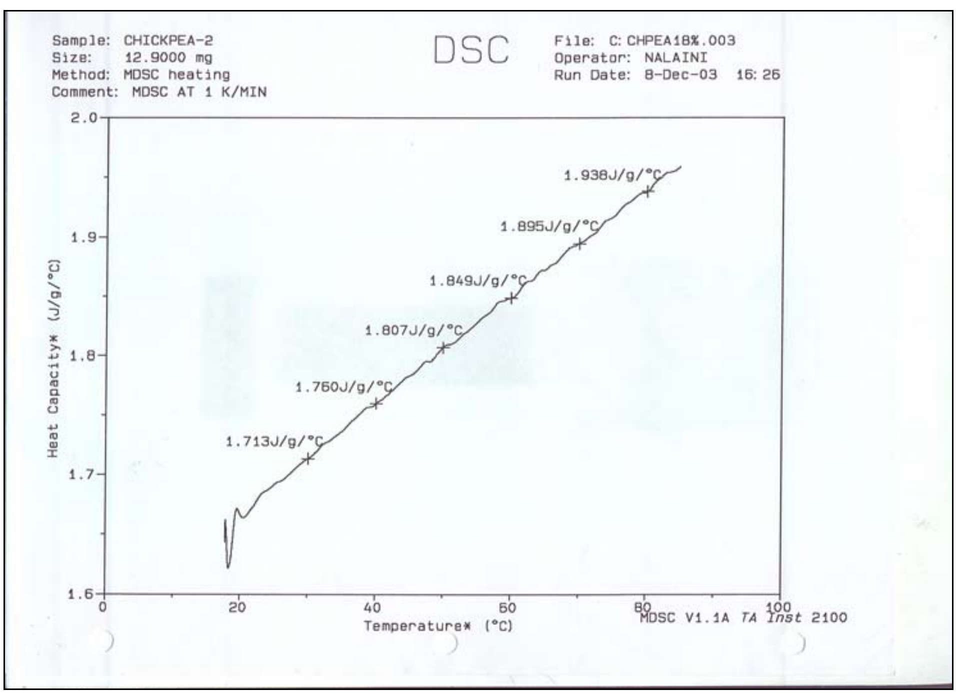

Figure A2. Specific heat values of chickpea seed sample at 18.17% w.b moisture content.

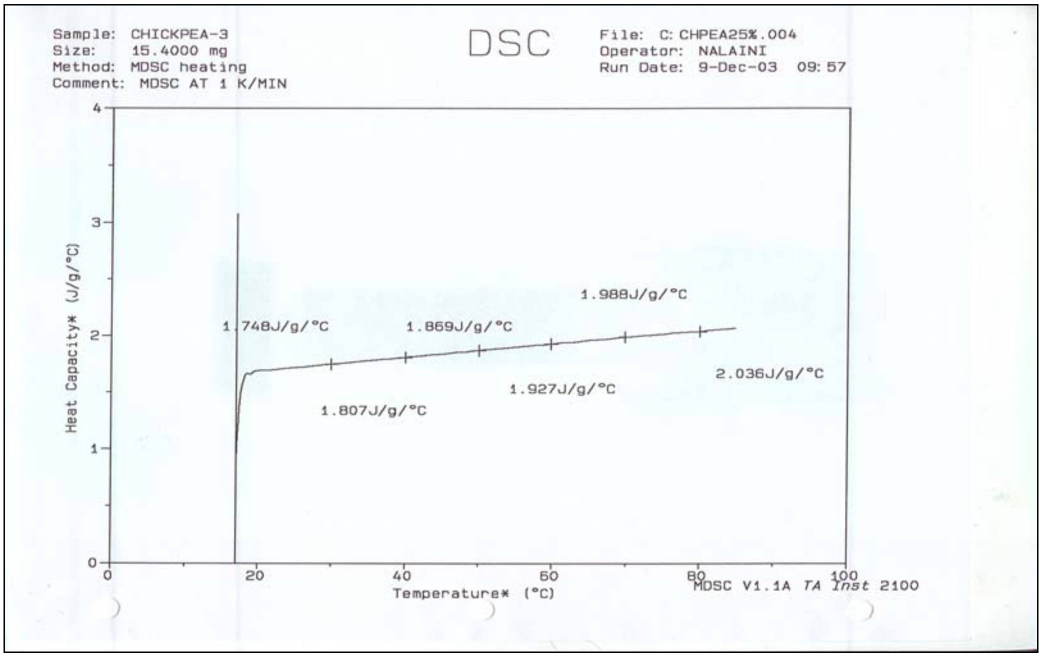

Figure A3. Specific heat values of chickpea seed sample at 25.10% w.b moisture content.

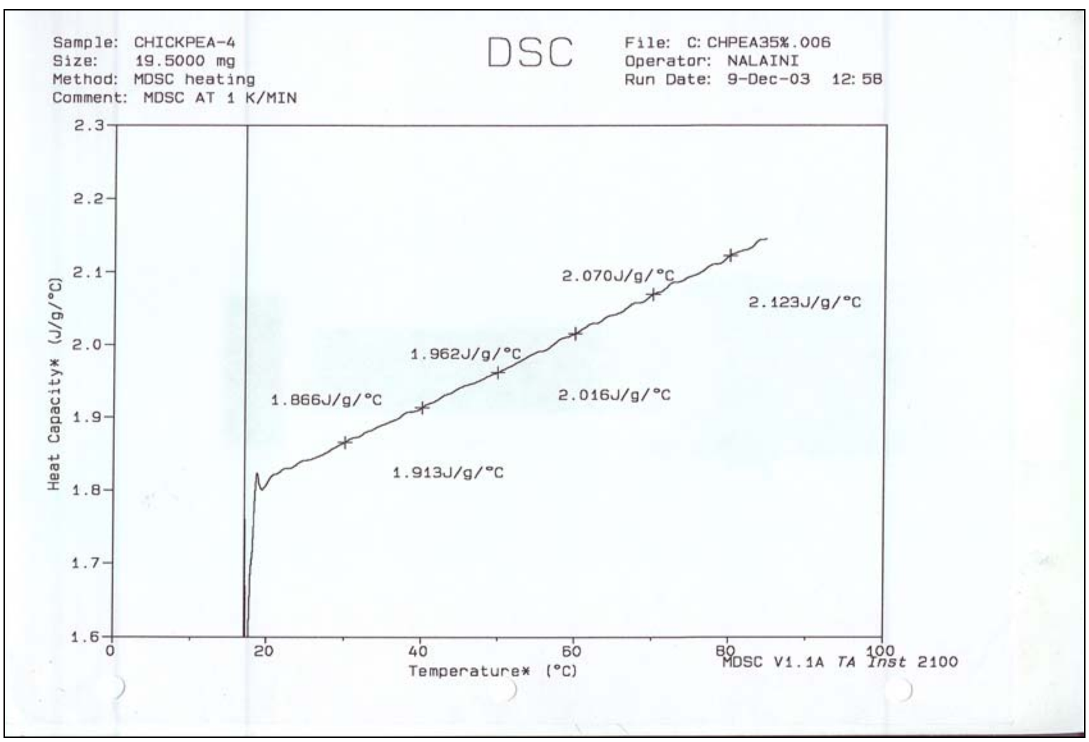

Figure A4. Specific heat values of chickpea seed sample at 35.89% w.b moisture content.

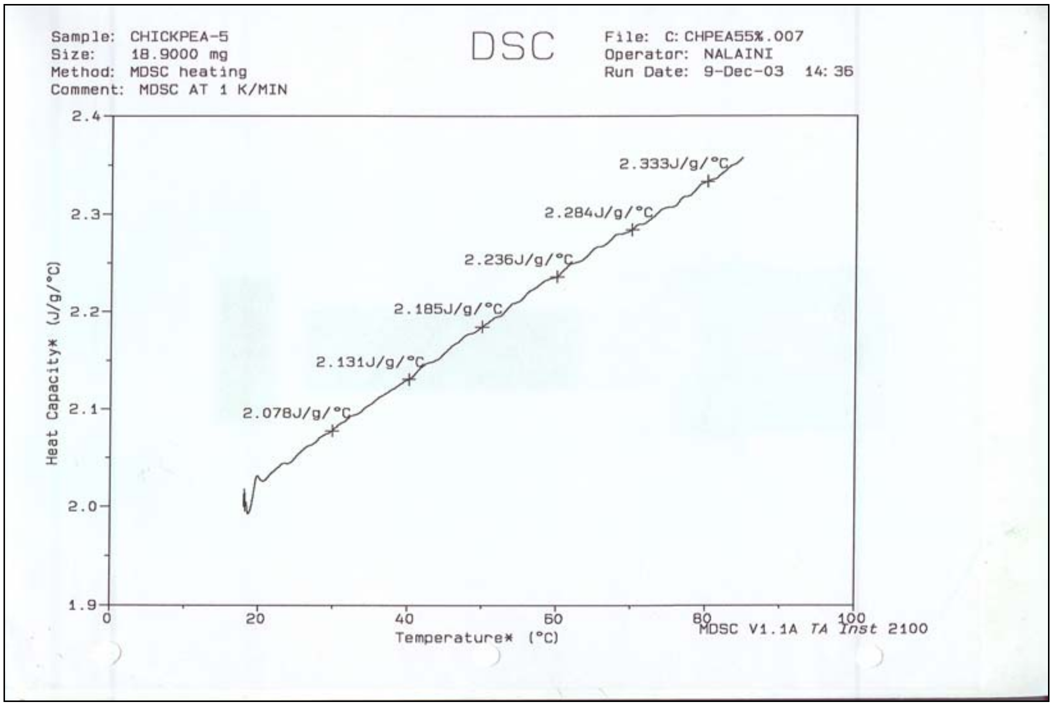

Figure A5. Specific heat values of chickpea seed sample at 55.97% w.b moisture content.

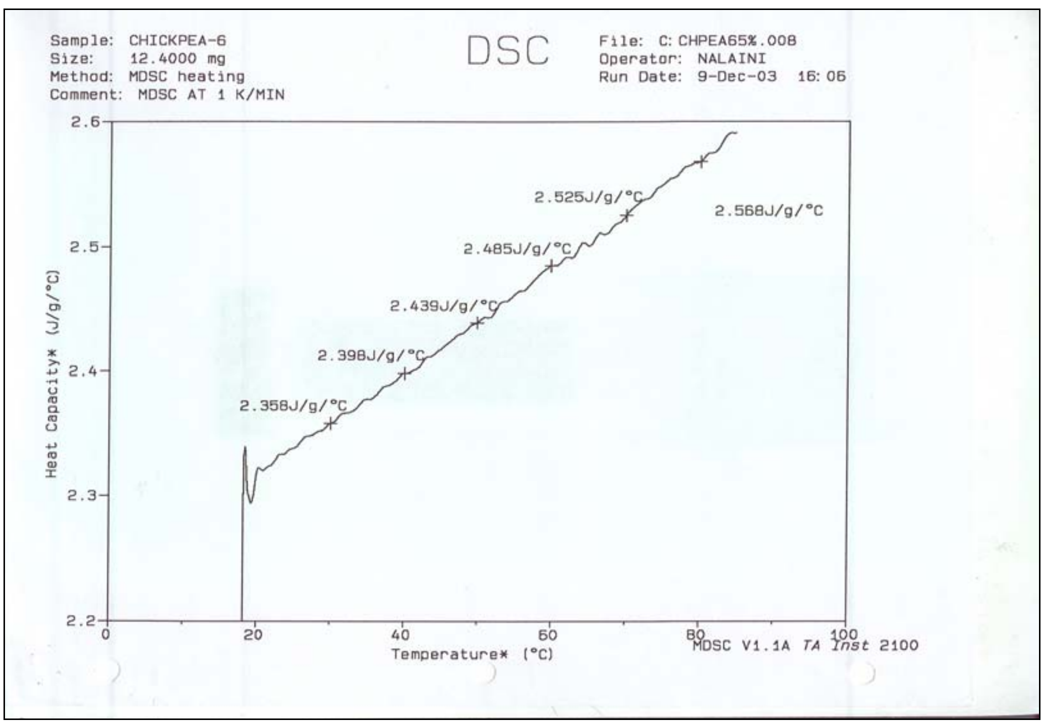

Figure A6. Specific heat values of chickpea seed sample at 65.24% w.b moisture content.

APPENDIX B

Simulation programs used to predict the heat and mass transfer during cooking of chickpea.

Program 1: Program used for simulating the soaked chickpea when cooked at 70°C

```
:HEAT AND MASS TRANSFER DURING COOKING OF CHICKPEA(h70sk.sim)
:Temperature and moisture distribution for 70 degree soaked seeds
:DM=Moisture diffusivity, m^2/s
:ALPHA=Thermal diffusivity, m^2/s
:H=Heat transfer coefficient, W/m^2.K
:K= Thermal conductivity of chickpea, W/mK
:M*=Moisture concentration, db
:MS=Moisture concentration at product surface, db
:T*= Temperature, C
:TA=Ambient temperature, C
:TS=Surface temperature, C


:INITIAL CONDITIONS
CONSTANT ALPHA=2.24E-7, K=0.2632, H=212
CONSTANT DM=8.53E-11
CONSTANT MS=0.01, DR=0.005,T0=24.84,M0=1
CONSTANT TFIN=250, CINT=0.125, TA=69.20

1 SIM;INTERACT;RESET;GOTO 1
INITIAL

T1=24.84
T2=24.84
T3=24.84
T4=24.84
T5=24.84
T6=24.84
T7=24.84
T8=24.84
T9=24.84
T10=24.84
TS=24.84

M1=1
M2=1
M3=1
M4=1
```

```
M5=1
M6=1
M7=1
M8=1
M9=1
M10=1


DYNAMIC
ADR2=100*ALPHA/(DR*DR)
DDR2=100*DM/(DR*DR)
T0'=3*ADR2*(T1-T0)
T1'=ADR2*(3*T2-2*T1-T0)
T2'=ADR2*(1.6667*T3-2*T2+0.3333*T1)
T3'=ADR2*(1.4000*T4-2*T3+0.6000*T2)
T4'=ADR2*(1.2857*T5-2*T4+0.7143*T3)
T5'=ADR2*(1.2222*T6-2*T5+0.7778*T4)
T6'=ADR2*(1.1818*T7-2*T6+0.8182*T5)
T7'=ADR2*(1.1538*T8-2*T7+0.8462*T6)
T8'=ADR2*(1.1333*T9-2*T8+0.8667*T7)
T9'=ADR2*(1.1176*T10-2*T9+0.8824*T8)
T10'=4*ADR2*(40/57*TS-T10+17/57*T9)

M0'=3*DDR2*(M1-M0)
M1'=DDR2*(3*M2-2*M1-M0)
M2'=DDR2*(1.6667*M3-2*M2+0.3333*M1)
M3'=DDR2*(1.4000*M4-2*M3+0.6000*M2)
M4'=DDR2*(1.2857*M5-2*M4+0.7143*M3)
M5'=DDR2*(1.2222*M6-2*M5+0.7778*M4)
M6'=DDR2*(1.1818*M7-2*M6+0.8182*M5)
M7'=DDR2*(1.1538*M8-2*M7+0.8462*M6)
M8'=DDR2*(1.1333*M9-2*M8+0.8667*M7)
M9'=DDR2*(1.1176*M10-2*M9+0.8824*M8)
M10'=4*DDR2*(40/57*MS-M10+17/57*M9)

MAVE=(M0+M1+M2+M3+M4+M5+M6+M7+M8+M9+M10)/10
TS=(0.5*DR*H/K*TA+T10)/(1+0.5*DR*H/K)
PLOT T,TS,0,TFIN,0,100
OUTPUT T,T0,T1,TS,M1,M2,MAVE
PREPARE T,T0,T1,TS,M1,M2,MAVE
```

Program 2: Program used for simulating the unsoaked chickpea when cooked at 70°C

```
:HEAT AND MASS TRANSFER DURING COOKING OF CHICKPEA(h70unsk.sim)
:Temperature and moisture distribution for 70 degree unsoaked seeds
:DM=Moisture diffusivity, m^2/s
:ALPHA=Thermal diffusivity, m^2/s
:H=Heat transfer coefficient, W/m^2.K
:K= Thermal conductivity of chickpea, W/mK
:M*=Moisture concentration, db
:MS=Moisture concentration at product surface, db
:T*= Temperature, C
:TA=Ambient temperature, C
:TS=Surface temperature, C


:INITIAL CONDITIONS
CONSTANT ALPHA=7.36E-8, K=0.1886, H=212
CONSTANT DM=4.13E-11
CONSTANT MS=0.01, DR=0.005,T0=24.84,M0=1
CONSTANT TFIN=250, CINT=0.125, TA=69.20

1 SIM;INTERACT;RESET;GOTO 1
INITIAL

T1=24.84
T2=24.84
T3=24.84
T4=24.84
T5=24.84
T6=24.84
T7=24.84
T8=24.84
T9=24.84
T10=24.84
TS=24.84

M1=1
M2=1
M3=1
M4=1
M5=1
M6=1
M7=1
M8=1
M9=1
M10=1
```

```
DYNAMIC
ADR2=100*ALPHA/(DR*DR)
DDR2=100*DM/(DR*DR)
T0'=3*ADR2*(T1-T0)
T1'=ADR2*(3*T2-2*T1-T0)
T2'=ADR2*(1.6667*T3-2*T2+0.3333*T1)
T3'=ADR2*(1.4000*T4-2*T3+0.6000*T2)
T4'=ADR2*(1.2857*T5-2*T4+0.7143*T3)
T5'=ADR2*(1.2222*T6-2*T5+0.7778*T4)
T6'=ADR2*(1.1818*T7-2*T6+0.8182*T5)
T7'=ADR2*(1.1538*T8-2*T7+0.8462*T6)
T8'=ADR2*(1.1333*T9-2*T8+0.8667*T7)
T9'=ADR2*(1.1176*T10-2*T9+0.8824*T8)
T10'=4*ADR2*(40/57*TS-T10+17/57*T9)

M0'=3*DDR2*(M1-M0)
M1'=DDR2*(3*M2-2*M1-M0)
M2'=DDR2*(1.6667*M3-2*M2+0.3333*M1)
M3'=DDR2*(1.4000*M4-2*M3+0.6000*M2)
M4'=DDR2*(1.2857*M5-2*M4+0.7143*M3)
M5'=DDR2*(1.2222*M6-2*M5+0.7778*M4)
M6'=DDR2*(1.1818*M7-2*M6+0.8182*M5)
M7'=DDR2*(1.1538*M8-2*M7+0.8462*M6)
M8'=DDR2*(1.1333*M9-2*M8+0.8667*M7)
M9'=DDR2*(1.1176*M10-2*M9+0.8824*M8)
M10'=4*DDR2*(40/57*MS-M10+17/57*M9)

MAVE=(M0+M1+M2+M3+M4+M5+M6+M7+M8+M9+M10)/10
TS=(0.5*DR*H/K*TA+T10)/(1+0.5*DR*H/K)
PLOT T,TS,0,TFIN,0,100
OUTPUT T,T0,T1,TS,M1,M2,MAVE
PREPARE T,T0,T1,TS,M1,M2,MAVE
```

APPENDIX C

Simulated Temperature History

Table C1. Temperature distribution of soaked chickpea at 70°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	55.34
0.125	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	25.09	56.59
0.250	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.87	25.51	35.60	61.94
0.375	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.85	25.02	27.03	42.65	65.36
0.500	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.89	25.35	28.91	47.35	65.87
0.625	24.84	24.84	24.84	24.84	24.84	24.84	24.85	24.97	25.83	30.88	50.59	66.26
0.750	24.84	24.84	24.84	24.84	24.84	24.84	24.87	25.09	26.45	32.81	52.87	66.58
0.875	24.84	24.84	24.84	24.84	24.84	24.85	24.91	25.28	27.17	34.63	54.54	66.85
1.000	24.84	24.84	24.84	24.84	24.84	24.86	24.96	25.51	27.97	36.31	55.79	67.21
2.375	24.85	24.86	24.87	24.93	25.12	25.67	27.11	30.44	37.01	47.63	61.14	67.48
6.250	27.05	27.56	27.96	29.13	31.14	34.20	38.47	43.98	50.52	57.61	64.56	67.59
7.625	29.30	29.99	30.50	31.95	34.30	37.63	41.96	47.20	53.09	59.22	65.07	67.71
9.000	32.08	32.87	33.42	35.01	37.48	40.83	45.01	49.86	55.12	60.45	65.46	67.71
10.375	35.10	35.93	36.48	38.08	40.53	43.77	47.67	52.09	56.78	61.44	65.78	67.71
11.875	38.42	39.24	39.77	41.31	43.64	46.64	50.21	54.16	58.28	62.32	66.05	67.71
14.375	43.62	44.35	44.82	46.17	48.18	50.73	53.71	56.94	60.26	63.47	66.41	67.71
16.875	48.13	48.74	49.14	50.27	51.94	54.06	56.49	59.11	61.78	64.35	66.68	67.71
18.125	50.10	50.66	51.02	52.04	53.56	55.47	57.66	60.02	62.41	64.71	66.79	67.71
24.375	57.46	57.80	58.01	58.62	59.51	60.64	61.92	63.29	64.67	65.99	67.19	67.71
30.750	61.85	62.04	62.16	62.51	63.03	63.67	64.41	65.19	65.98	66.73	67.41	67.71
36.875	64.29	64.40	64.47	64.68	64.98	65.36	65.78	66.24	66.70	67.14	67.54	67.71
43.125	65.74	65.80	65.84	65.96	66.14	66.35	66.60	66.86	67.13	67.38	67.61	67.71
49.375	66.57	66.61	66.64	66.70	66.80	66.93	67.07	67.22	67.38	67.52	67.66	67.71
55.625	67.06	67.08	67.09	67.13	67.19	67.26	67.34	67.43	67.52	67.61	67.68	67.71
61.875	67.34	67.35	67.36	67.38	67.41	67.45	67.50	67.55	67.60	67.65	67.70	67.71
68.125	67.50	67.50	67.51	67.52	67.54	67.56	67.59	67.62	67.65	67.68	67.70	67.71
74.375	67.59	67.59	67.60	67.60	67.61	67.63	67.64	67.66	67.68	67.69	67.71	67.71
80.625	67.64	67.64	67.65	67.65	67.66	67.66	67.67	67.68	67.69	67.70	67.71	67.71
86.875	67.67	67.67	67.68	67.68	67.68	67.69	67.69	67.70	67.70	67.71	67.71	67.71
99.375	67.70	67.70	67.70	67.70	67.70	67.71	67.71	67.71	67.71	67.71	67.71	67.71
105.620	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
111.870	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
118.120	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
124.380	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
130.630	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
136.880	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
143.130	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
149.370	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
155.630	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
161.880	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
168.130	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
174.380	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71

180.620	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
186.880	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
193.130	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
199.380	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
205.630	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
211.880	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
224.380	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
230.630	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
236.880	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71
249.380	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71	67.71

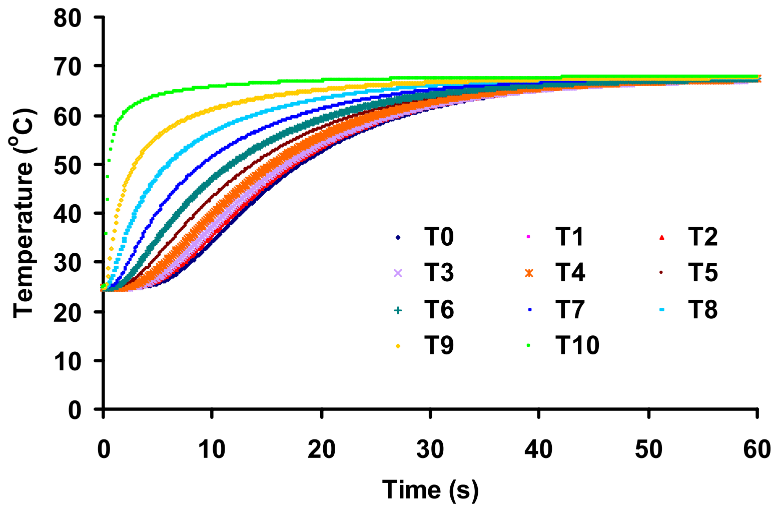

Figure C1. Simulated cooking curve for soaked kabuli chickpea at 70°C.

Table C2. Temperature distribution of unsoaked chickpea at 70°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	53.62
0.125	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.93	55.97
0.250	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.93	29.11	57.92
0.375	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.85	25.17	32.81	60.41
0.500	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.87	25.53	36.02	61.46
0.625	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.90	25.98	38.81	62.26
0.750	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.85	24.95	26.50	41.24	62.89
0.875	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.85	25.02	27.09	43.37	63.39
1.000	24.84	24.84	24.84	24.84	24.84	24.84	24.84	24.86	25.11	27.71	45.23	63.81
2.375	24.84	24.84	24.84	24.84	24.84	24.85	24.91	25.27	27.16	34.97	55.91	64.15
6.250	24.84	24.85	24.86	24.89	25.02	25.42	26.58	29.51	35.75	47.43	62.50	64.44
7.625	24.86	24.87	24.90	24.99	25.25	25.96	27.70	31.44	38.33	49.90	63.42	64.69

9.000	24.89	24.93	24.98	25.16	25.61	26.68	28.98	33.35	40.59	51.85	64.12	64.72
10.375	24.96	25.04	25.13	25.42	26.10	27.55	30.34	35.19	42.56	53.45	64.67	65.27
11.875	25.10	25.24	25.38	25.83	26.78	28.62	31.87	37.07	44.43	54.90	65.17	65.77
14.375	25.54	25.81	26.05	26.78	28.18	30.59	34.41	39.91	47.07	56.84	65.81	66.41
16.875	26.29	26.71	27.05	28.05	29.84	32.68	36.83	42.40	49.23	58.35	66.31	66.91
18.125	26.79	27.27	27.65	28.78	30.73	33.73	37.98	43.53	50.17	59.00	66.52	67.12
24.375	30.25	30.99	31.51	33.03	35.46	38.83	43.13	48.25	53.92	61.48	67.32	67.92
30.750	34.75	35.58	36.13	37.74	40.21	43.46	47.42	51.89	56.65	63.22	67.87	68.47
36.875	39.21	40.01	40.54	42.06	44.35	47.30	50.78	54.63	58.63	64.46	68.26	68.86
43.125	43.46	44.19	44.67	46.03	48.05	50.63	53.62	56.88	60.22	65.44	68.56	69.16
49.375	47.25	47.89	48.30	49.48	51.22	53.43	55.97	58.71	61.51	66.22	68.81	69.41
55.625	50.52	51.07	51.42	52.43	53.91	55.78	57.92	60.22	62.55	66.85	69.00	69.60
61.875	53.31	53.77	54.07	54.92	56.17	57.74	59.54	61.47	63.42	67.38	69.16	69.76
68.125	55.66	56.05	56.30	57.02	58.07	59.39	60.90	62.51	64.13	67.81	69.30	69.89
74.375	57.64	57.97	58.18	58.78	59.66	60.76	62.02	63.37	64.72	68.17	69.41	69.97
80.625	59.30	59.57	59.75	60.25	60.99	61.91	62.96	64.09	65.22	68.46	69.50	69.97
86.875	60.69	60.92	61.06	61.48	62.10	62.87	63.75	64.69	65.63	68.71	69.58	69.97
99.375	62.81	62.97	63.08	63.37	63.80	64.34	64.95	65.60	66.26	69.09	69.70	69.97
105.620	63.62	63.76	63.84	64.09	64.45	64.89	65.41	65.95	66.50	69.24	69.74	69.97
111.870	64.30	64.41	64.48	64.69	64.99	65.36	65.79	66.24	66.70	69.36	69.78	69.97
118.120	64.86	64.96	65.02	65.19	65.44	65.75	66.11	66.49	66.87	69.46	69.81	69.97
124.380	65.33	65.41	65.46	65.60	65.81	66.07	66.37	66.69	67.01	69.54	69.83	69.97
130.630	65.73	65.79	65.83	65.95	66.13	66.34	66.59	66.86	67.13	69.61	69.86	69.97
136.880	66.05	66.11	66.14	66.24	66.39	66.57	66.78	67.00	67.22	69.67	69.87	69.97
143.130	66.33	66.37	66.40	66.49	66.61	66.76	66.93	67.12	67.30	69.72	69.89	69.97
149.370	66.56	66.60	66.62	66.69	66.79	66.92	67.06	67.22	67.37	69.76	69.90	69.97
155.630	66.75	66.78	66.80	66.86	66.94	67.05	67.17	67.30	67.43	69.79	69.91	69.97
161.880	66.91	66.93	66.95	67.00	67.07	67.16	67.26	67.37	67.48	69.82	69.92	69.97
168.130	67.04	67.06	67.08	67.12	67.18	67.25	67.33	67.42	67.52	69.85	69.93	69.97
174.380	67.15	67.17	67.18	67.22	67.27	67.33	67.40	67.47	67.55	69.87	69.93	69.97
180.620	67.25	67.26	67.27	67.30	67.34	67.39	67.45	67.51	67.58	69.88	69.94	69.97
186.880	67.32	67.34	67.34	67.37	67.40	67.44	67.49	67.55	67.60	69.90	69.94	69.97
193.130	67.39	67.40	67.40	67.42	67.45	67.49	67.53	67.57	67.62	69.91	69.95	69.97
199.380	67.44	67.45	67.46	67.47	67.50	67.53	67.56	67.60	67.63	69.92	69.95	69.97
205.630	67.49	67.49	67.50	67.51	67.53	67.56	67.59	67.62	67.65	69.93	69.95	69.97
211.880	67.52	67.53	67.53	67.55	67.56	67.58	67.61	67.63	67.66	69.93	69.96	69.97
224.380	67.58	67.59	67.59	67.60	67.61	67.62	67.64	67.66	67.68	69.94	69.96	69.97
230.630	67.60	67.61	67.61	67.62	67.63	67.64	67.65	67.67	67.68	69.95	69.96	69.97
236.880	67.62	67.63	67.63	67.63	67.64	67.65	67.66	67.67	67.69	69.95	69.96	69.97
249.380	67.65	67.65	67.65	67.66	67.66	67.67	67.68	67.69	67.70	69.95	69.96	69.97

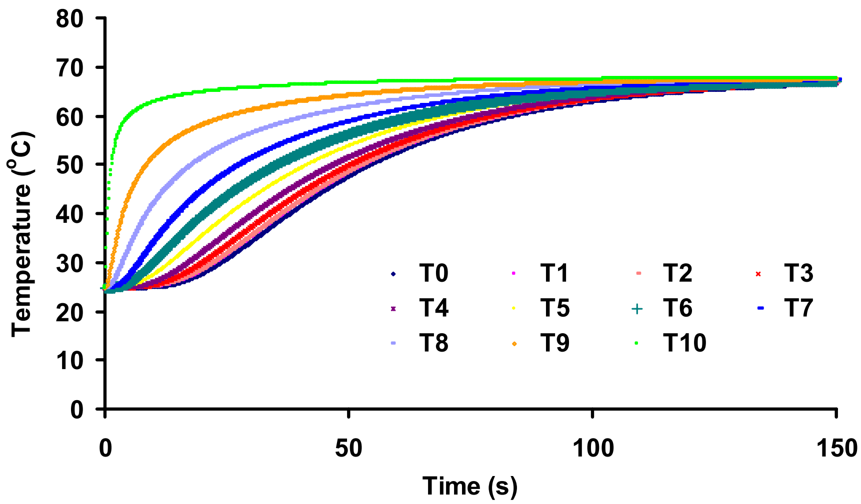

Figure C2. Simulated cooking curve for unsoaked kabuli chickpea at 70°C.

Table C3. Temperature distribution of soaked chickpea at 80°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	59.27
0.125	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	21.03	62.21
0.250	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.67	21.80	37.64	64.29
0.375	20.61	20.61	20.61	20.61	20.61	20.61	20.61	20.64	20.96	24.38	48.06	65.85
0.500	20.61	20.61	20.61	20.61	20.61	20.61	20.62	20.71	21.56	27.45	54.63	72.47
0.625	20.61	20.61	20.61	20.61	20.61	20.61	20.64	20.87	22.43	30.58	58.93	76.75
0.750	20.61	20.61	20.61	20.61	20.61	20.62	20.68	21.12	23.51	33.54	61.87	77.39
0.875	20.61	20.61	20.61	20.61	20.61	20.63	20.76	21.47	24.73	36.26	63.95	77.88
1.000	20.61	20.61	20.61	20.61	20.62	20.66	20.87	21.91	26.05	38.73	65.51	78.27
2.375	20.63	20.66	20.70	20.83	21.23	22.27	24.79	30.12	39.80	54.43	72.13	78.61
6.250	25.25	26.12	26.76	28.64	31.75	36.27	42.33	49.85	58.49	67.62	76.41	79.06
7.625	29.30	30.38	31.13	33.30	36.72	41.42	47.35	54.31	61.94	69.72	77.05	79.39
9.000	33.94	35.09	35.87	38.11	41.55	46.11	51.66	57.95	64.65	71.34	77.54	79.52
10.375	38.70	39.84	40.60	42.77	46.05	50.31	55.36	60.98	66.85	72.62	77.93	79.79
11.875	43.71	44.78	45.48	47.49	50.49	54.34	58.83	63.75	68.83	73.76	78.27	80.05
14.375	51.15	52.06	52.64	54.32	56.80	59.93	63.54	67.44	71.41	75.24	78.72	80.18
16.875	57.30	58.03	58.50	59.85	61.83	64.33	67.19	70.26	73.37	76.35	79.05	80.20
18.125	59.90	60.55	60.97	62.17	63.94	66.16	68.70	71.42	74.17	76.80	79.18	80.20
24.375	69.18	69.54	69.77	70.43	71.40	72.61	73.99	75.46	76.95	78.37	79.65	80.20
30.750	74.31	74.50	74.63	74.98	75.50	76.15	76.88	77.67	78.46	79.22	79.91	80.20
36.875	76.98	77.08	77.15	77.34	77.63	77.98	78.38	78.82	79.25	79.66	80.04	80.20
43.125	78.46	78.51	78.55	78.65	78.81	79.00	79.22	79.45	79.69	79.91	80.11	80.20
49.375	79.26	79.29	79.31	79.36	79.45	79.55	79.67	79.80	79.92	80.04	80.15	80.20
55.625	79.69	79.71	79.72	79.75	79.79	79.85	79.91	79.98	80.05	80.12	80.17	80.20

61.875	79.92	79.93	79.94	79.96	79.98	80.01	80.04	80.08	80.12	80.15	80.19	80.20
68.125	80.05	80.06	80.06	80.07	80.08	80.10	80.12	80.14	80.16	80.18	80.19	80.20
74.375	80.12	80.12	80.12	80.13	80.14	80.14	80.15	80.17	80.18	80.19	80.20	80.20
80.625	80.16	80.16	80.16	80.16	80.17	80.17	80.18	80.18	80.19	80.19	80.20	80.20
86.875	80.18	80.18	80.18	80.18	80.18	80.18	80.19	80.19	80.19	80.20	80.20	80.20
99.375	80.19	80.19	80.19	80.19	80.19	80.20	80.20	80.20	80.20	80.20	80.20	80.20
105.620	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
111.870	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
118.120	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
124.380	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
130.630	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
136.880	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
143.130	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
149.370	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
155.630	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
161.880	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
168.130	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
174.380	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
180.620	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
186.880	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
193.130	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
199.380	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
205.630	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
211.880	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
224.380	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
230.630	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
236.880	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20
249.380	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20	80.20

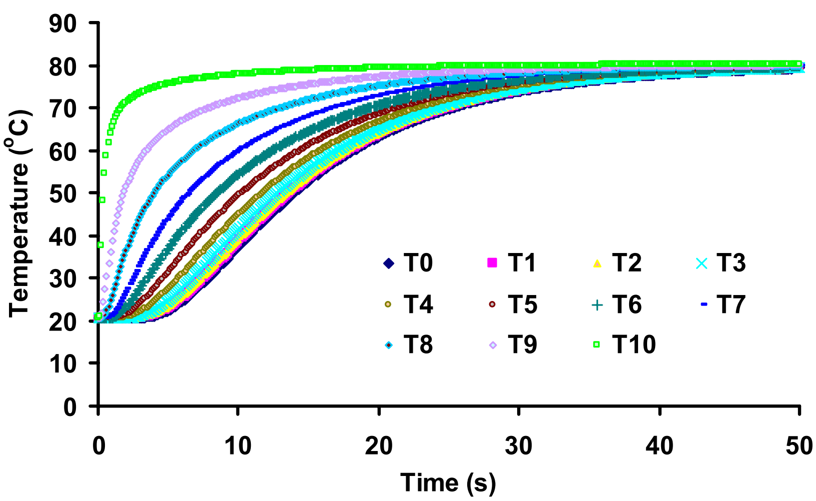

Figure C3. Simulated cooking curve for soaked kabuli chickpea at 80°C.

Table C4. Temperature distribution of unsoaked chickpea at 80°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	67.23
0.125	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	24.08	72.56
0.250	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	24.11	32.86	73.32
0.375	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.90	24.70	39.24	73.91
0.500	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.96	25.51	44.18	74.39
0.625	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.88	24.06	26.47	48.14	74.83
0.750	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.89	24.20	27.53	51.38	75.42
0.875	23.87	23.87	23.87	23.87	23.87	23.87	23.87	23.91	24.38	28.65	54.06	75.90
1.000	23.87	23.87	23.87	23.87	23.87	23.87	23.88	23.94	24.60	29.79	56.28	76.11
2.375	23.87	23.87	23.87	23.87	23.88	23.91	24.10	25.04	28.93	41.07	66.88	76.92
6.250	23.90	23.92	23.96	24.10	24.50	25.54	28.01	33.17	42.39	56.05	72.21	77.50
7.625	23.97	24.04	24.13	24.43	25.17	26.82	30.18	36.27	45.86	58.71	72.97	77.91
9.000	24.14	24.29	24.45	24.97	26.11	28.37	32.47	39.15	48.77	60.79	73.56	78.23
10.375	24.45	24.71	24.96	25.73	27.28	30.09	34.76	41.79	51.25	62.47	74.04	78.48
11.875	24.99	25.39	25.74	26.79	28.77	32.08	37.20	44.40	53.56	64.00	74.48	78.68
14.375	26.42	27.06	27.56	29.03	31.58	35.49	41.02	48.20	56.75	66.02	75.07	78.83
16.875	28.46	29.28	29.90	31.68	34.62	38.86	44.49	51.43	59.33	67.62	75.55	78.96
18.125	29.66	30.56	31.21	33.11	36.17	40.49	46.10	52.87	60.45	68.30	75.76	79.06
24.375	36.67	37.75	38.47	40.55	43.73	47.93	53.02	58.77	64.87	70.94	76.57	79.10
30.750	44.12	45.13	45.79	47.69	50.54	54.20	58.49	63.19	68.06	72.80	77.15	79.10
36.875	50.54	51.42	51.99	53.62	56.03	59.08	62.62	66.44	70.35	74.12	77.56	79.10
43.125	56.09	56.82	57.29	58.63	60.61	63.10	65.96	69.04	72.16	75.16	77.88	79.10
49.375	60.65	61.25	61.62	62.71	64.31	66.32	68.62	71.09	73.58	75.97	78.13	79.10
55.625	64.34	64.82	65.12	66.00	67.29	68.90	70.74	72.71	74.70	76.60	78.33	79.10
61.875	67.31	67.69	67.93	68.64	69.67	70.96	72.43	74.01	75.59	77.11	78.48	79.10
68.125	69.68	69.99	70.18	70.75	71.57	72.60	73.78	75.04	76.30	77.51	78.61	79.10
74.375	71.58	71.83	71.98	72.43	73.09	73.91	74.85	75.86	76.87	77.83	78.71	79.10
80.625	73.10	73.29	73.42	73.78	74.30	74.96	75.71	76.51	77.32	78.09	78.79	79.10
86.875	74.31	74.47	74.57	74.85	75.27	75.80	76.40	77.04	77.68	78.29	78.85	79.10
99.375	76.05	76.15	76.21	76.39	76.66	77.00	77.38	77.79	78.20	78.59	78.94	79.10
105.620	76.67	76.75	76.80	76.94	77.15	77.42	77.73	78.05	78.38	78.69	78.97	79.10
111.870	77.16	77.22	77.26	77.38	77.55	77.76	78.00	78.26	78.52	78.77	79.00	79.10
118.120	77.55	77.60	77.63	77.73	77.86	78.03	78.23	78.43	78.64	78.84	79.02	79.10
124.380	77.86	77.90	77.93	78.00	78.11	78.25	78.40	78.57	78.73	78.89	79.04	79.10
130.630	78.11	78.15	78.17	78.22	78.31	78.42	78.54	78.67	78.81	78.93	79.05	79.10
136.880	78.31	78.34	78.35	78.40	78.47	78.56	78.66	78.76	78.87	78.97	79.06	79.10
143.130	78.47	78.49	78.51	78.54	78.60	78.67	78.75	78.83	78.91	78.99	79.07	79.10
149.370	78.60	78.61	78.63	78.66	78.70	78.75	78.82	78.88	78.95	79.02	79.07	79.10
155.630	78.70	78.71	78.72	78.75	78.78	78.82	78.87	78.93	78.98	79.03	79.08	79.10
161.880	78.78	78.79	78.80	78.82	78.85	78.88	78.92	78.96	79.01	79.05	79.08	79.10
168.130	78.85	78.85	78.86	78.87	78.90	78.92	78.96	78.99	79.02	79.06	79.09	79.10
174.380	78.90	78.90	78.91	78.92	78.94	78.96	78.99	79.01	79.04	79.07	79.09	79.10
180.620	78.94	78.94	78.95	78.96	78.97	78.99	79.01	79.03	79.05	79.07	79.09	79.10
186.880	78.97	78.98	78.98	78.99	79.00	79.01	79.03	79.04	79.06	79.08	79.09	79.10
193.130	79.00	79.00	79.00	79.01	79.02	79.03	79.04	79.06	79.07	79.08	79.10	79.10
199.380	79.02	79.02	79.02	79.03	79.03	79.04	79.05	79.06	79.08	79.09	79.10	79.10

205.630	79.03	79.04	79.04	79.04	79.05	79.06	79.06	79.07	79.08	79.09	79.10	79.10
211.880	79.05	79.05	79.05	79.05	79.06	79.06	79.07	79.08	79.08	79.09	79.10	79.10
224.380	79.07	79.07	79.07	79.07	79.07	79.08	79.08	79.09	79.09	79.09	79.10	79.10
230.630	79.07	79.07	79.08	79.08	79.08	79.08	79.09	79.09	79.09	79.10	79.10	79.10
236.880	79.08	79.08	79.08	79.08	79.08	79.09	79.09	79.09	79.09	79.10	79.10	79.10
249.380	79.09	79.09	79.09	79.09	79.09	79.09	79.09	79.09	79.10	79.10	79.10	79.10

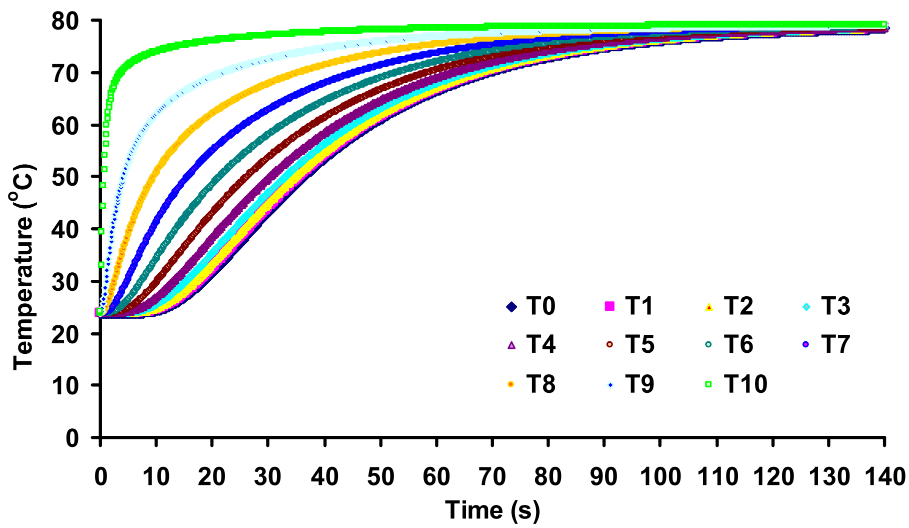

Figure C4. Simulated cooking curve for unsoaked kabuli chickpea at 80°C.

Table C5. Temperature distribution of soaked chickpea at 90°C.

Time (s)	Temperature (°C)											
	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	65.98
0.125	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	21.06	69.27
0.250	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.61	21.98	40.95	71.61
0.375	20.54	20.54	20.54	20.54	20.54	20.54	20.54	20.57	20.97	25.05	52.90	73.36
0.500	20.54	20.54	20.54	20.54	20.54	20.54	20.55	20.66	21.68	28.65	60.33	80.74
0.625	20.54	20.54	20.54	20.54	20.54	20.54	20.58	20.85	22.71	32.28	65.18	85.49
0.750	20.54	20.54	20.54	20.54	20.54	20.55	20.63	21.15	23.97	35.71	68.47	85.86
0.875	20.54	20.54	20.54	20.54	20.54	20.57	20.72	21.56	25.41	38.86	70.81	86.42
1.000	20.54	20.54	20.54	20.54	20.55	20.59	20.85	22.08	26.94	41.70	72.56	86.86
2.375	20.57	20.60	20.64	20.81	21.27	22.50	25.44	31.63	42.83	59.66	79.94	87.26
6.250	25.98	26.99	27.74	29.91	33.51	38.73	45.70	54.34	64.23	74.67	84.69	87.35
7.625	30.70	31.94	32.80	35.31	39.25	44.66	51.46	59.44	68.17	77.05	85.41	87.74
9.000	36.06	37.39	38.28	40.86	44.81	50.05	56.40	63.60	71.26	78.89	85.97	87.91
10.375	41.56	42.87	43.74	46.23	49.99	54.86	60.65	67.07	73.77	80.36	86.41	88.47
11.875	47.32	48.55	49.35	51.65	55.09	59.48	64.62	70.24	76.03	81.66	86.81	88.78
14.375	55.87	56.91	57.57	59.49	62.31	65.89	70.01	74.46	78.99	83.36	87.32	88.94
16.875	62.91	63.75	64.28	65.82	68.08	70.93	74.19	77.69	81.23	84.63	87.71	89.03
18.125	65.89	66.64	67.11	68.48	70.50	73.03	75.92	79.02	82.15	85.16	87.88	89.07
24.375	76.49	76.91	77.17	77.92	79.02	80.40	81.98	83.66	85.35	86.97	88.44	89.10

30.750	82.36	82.58	82.72	83.12	83.71	84.45	85.29	86.19	87.10	87.96	88.75	89.10
36.875	85.41	85.53	85.61	85.83	86.15	86.55	87.02	87.51	88.00	88.48	88.91	89.10
43.125	87.10	87.17	87.21	87.33	87.50	87.72	87.97	88.24	88.51	88.76	89.00	89.10
49.375	88.02	88.05	88.08	88.14	88.24	88.35	88.49	88.63	88.78	88.92	89.04	89.10
55.625	88.52	88.53	88.55	88.58	88.63	88.70	88.77	88.85	88.93	89.00	89.07	89.10
61.875	88.78	88.79	88.80	88.82	88.85	88.88	88.92	88.96	89.01	89.05	89.08	89.10
68.125	88.93	88.93	88.94	88.95	88.96	88.98	89.00	89.03	89.05	89.07	89.09	89.10
74.375	89.01	89.01	89.01	89.02	89.03	89.04	89.05	89.06	89.07	89.08	89.10	89.10
80.625	89.05	89.05	89.05	89.06	89.06	89.07	89.07	89.08	89.09	89.09	89.10	89.10
86.875	89.07	89.07	89.07	89.08	89.08	89.08	89.09	89.09	89.09	89.10	89.10	89.10
99.375	89.09	89.09	89.09	89.09	89.09	89.10	89.10	89.10	89.10	89.10	89.10	89.10
105.620	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
111.870	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
118.120	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
124.380	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
130.630	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
136.880	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
143.130	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
149.370	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
155.630	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
161.880	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
168.130	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
174.380	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
180.620	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
186.880	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
193.130	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
199.380	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
205.630	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
211.880	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
224.380	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
230.630	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
236.880	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10
249.380	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10	89.10

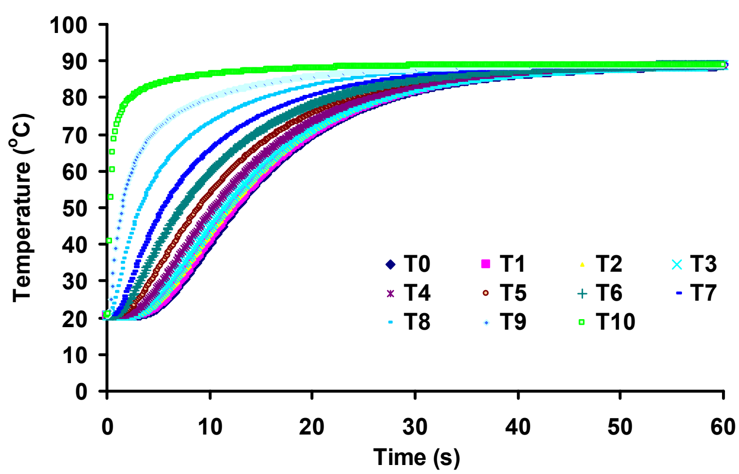

Figure C5. Simulated cooking curve for soaked kabuli chickpea at 90°C.

Table C6. Temperature distribution of unsoaked chickpea at 90°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	62.74
0.125	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	27.43	65.72
0.250	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.52	27.10	44.07	67.96
0.375	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.58	28.23	52.35	69.67
0.500	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.52	26.71	29.62	57.97	76.55
0.625	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.53	26.90	31.14	62.00	82.39
0.750	26.51	26.51	26.51	26.51	26.51	26.51	26.51	26.56	27.16	32.70	64.98	83.42
0.875	26.51	26.51	26.51	26.51	26.51	26.51	26.52	26.60	27.48	34.27	67.22	84.22
1.000	26.51	26.51	26.51	26.51	26.51	26.51	26.52	26.66	27.86	35.81	68.93	84.86
2.375	26.51	26.51	26.51	26.51	26.52	26.59	26.93	28.46	33.93	48.78	76.10	85.44
6.250	26.57	26.63	26.70	26.95	27.59	29.15	32.51	38.96	49.66	64.66	81.94	86.20
7.625	26.72	26.86	27.02	27.51	28.63	30.94	35.30	42.65	53.59	67.64	82.97	86.78
9.000	27.05	27.31	27.57	28.36	29.99	33.02	38.15	46.05	56.89	70.00	83.77	87.03
10.375	27.61	28.02	28.39	29.51	31.63	35.27	40.97	49.13	59.70	71.93	84.41	87.98
11.875	28.52	29.11	29.60	31.05	33.65	37.81	43.92	52.17	62.34	73.68	84.99	88.41
14.375	30.74	31.60	32.25	34.16	37.35	42.07	48.49	56.58	65.98	76.01	85.75	88.87
16.875	33.67	34.73	35.49	37.69	41.23	46.20	52.61	60.31	68.93	77.84	86.33	89.22
18.125	35.33	36.46	37.25	39.55	43.17	48.17	54.51	61.98	70.20	78.62	86.58	89.49
24.375	44.47	45.70	46.51	48.85	52.40	57.03	62.56	68.73	75.21	81.61	87.53	89.69
30.750	53.53	54.63	55.33	57.38	60.42	64.30	68.81	73.73	78.79	83.70	88.18	89.86
36.875	61.00	61.92	62.50	64.19	66.68	69.83	73.45	77.36	81.33	85.16	88.64	89.80
43.125	67.24	67.97	68.44	69.79	71.78	74.28	77.14	80.20	83.31	86.29	88.99	89.88
49.375	72.21	72.79	73.16	74.23	75.79	77.76	80.00	82.41	84.83	87.15	89.26	89.96
55.625	76.13	76.58	76.87	77.71	78.94	80.48	82.24	84.12	86.01	87.82	89.46	90.02
61.875	79.20	79.56	79.79	80.44	81.41	82.61	83.99	85.45	86.93	88.35	89.63	90.10
68.125	81.61	81.89	82.07	82.58	83.33	84.27	85.35	86.49	87.65	88.75	89.75	90.13
74.375	83.49	83.71	83.85	84.25	84.84	85.57	86.41	87.31	88.21	89.07	89.85	90.15
80.625	84.96	85.13	85.24	85.55	86.01	86.59	87.24	87.94	88.65	89.32	89.93	90.17
86.875	86.11	86.24	86.33	86.57	86.93	87.38	87.89	88.44	88.99	89.51	89.99	90.18
99.375	87.71	87.79	87.84	87.99	88.21	88.48	88.79	89.12	89.46	89.78	90.07	90.19
105.620	88.25	88.32	88.36	88.47	88.64	88.86	89.10	89.36	89.62	89.87	90.10	90.20
111.870	88.68	88.73	88.76	88.85	88.98	89.15	89.34	89.54	89.75	89.94	90.12	90.20
118.120	89.01	89.05	89.08	89.15	89.25	89.38	89.53	89.69	89.85	90.00	90.14	90.20
124.380	89.27	89.30	89.32	89.38	89.46	89.56	89.68	89.80	89.93	90.04	90.15	90.20
130.630	89.48	89.50	89.51	89.56	89.62	89.70	89.79	89.89	89.99	90.08	90.16	90.20
136.880	89.63	89.65	89.67	89.70	89.75	89.81	89.88	89.96	90.03	90.11	90.17	90.20
143.130	89.76	89.77	89.78	89.81	89.85	89.90	89.95	90.01	90.07	90.13	90.18	90.20
149.370	89.86	89.87	89.87	89.89	89.92	89.96	90.01	90.05	90.10	90.14	90.18	90.20
155.630	89.93	89.94	89.95	89.96	89.99	90.01	90.05	90.08	90.12	90.16	90.19	90.20
161.880	89.99	90.00	90.00	90.01	90.03	90.06	90.08	90.11	90.14	90.17	90.19	90.20
168.130	90.04	90.04	90.05	90.05	90.07	90.09	90.11	90.13	90.15	90.17	90.19	90.20
174.380	90.07	90.08	90.08	90.09	90.10	90.11	90.13	90.15	90.16	90.18	90.19	90.20
180.620	90.10	90.10	90.11	90.11	90.12	90.13	90.14	90.16	90.17	90.18	90.20	90.20
186.880	90.12	90.12	90.13	90.13	90.14	90.15	90.16	90.17	90.18	90.19	90.20	90.20
193.130	90.14	90.14	90.14	90.15	90.15	90.16	90.17	90.17	90.18	90.19	90.20	90.20
199.380	90.15	90.15	90.16	90.16	90.16	90.17	90.17	90.18	90.19	90.19	90.20	90.20
205.630	90.16	90.16	90.17	90.17	90.17	90.17	90.18	90.18	90.19	90.19	90.20	90.20
211.880	90.17	90.17	90.17	90.17	90.18	90.18	90.18	90.19	90.19	90.20	90.20	90.20

224.380	90.18	90.18	90.18	90.18	90.19	90.19	90.19	90.19	90.20	90.20	90.20	90.20
230.630	90.19	90.19	90.19	90.19	90.19	90.19	90.19	90.19	90.20	90.20	90.20	90.20
236.880	90.19	90.19	90.19	90.19	90.19	90.19	90.19	90.20	90.20	90.20	90.20	90.20
249.380	90.19	90.19	90.19	90.19	90.20	90.20	90.20	90.20	90.20	90.20	90.20	90.20

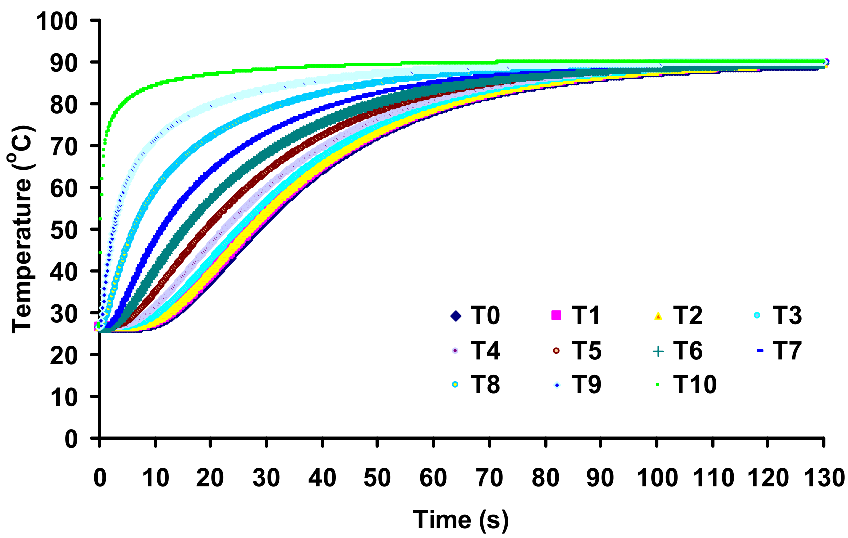

Figure C6. Simulated cooking curve for unsoaked kabuli chickpea at 90°C.

Table C7. Temperature distribution of soaked chickpea at 98°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	66.22
0.125	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	21.08	71.61
0.250	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.57	22.14	43.54	75.27
0.375	20.49	20.49	20.49	20.49	20.49	20.49	20.49	20.53	20.98	25.61	56.88	77.87
0.500	20.49	20.49	20.49	20.49	20.49	20.49	20.50	20.63	21.79	29.68	65.16	79.80
0.625	20.49	20.49	20.49	20.49	20.49	20.49	20.53	20.85	22.96	33.76	70.55	88.00
0.750	20.49	20.49	20.49	20.49	20.49	20.50	20.59	21.19	24.40	37.62	74.21	93.29
0.875	20.49	20.49	20.49	20.49	20.49	20.52	20.69	21.66	26.02	41.15	76.81	94.10
1.000	20.49	20.49	20.49	20.49	20.50	20.55	20.85	22.25	27.76	44.33	78.74	94.72
2.375	20.52	20.56	20.61	20.80	21.34	22.74	26.07	33.05	45.60	64.39	86.94	95.22
6.250	26.74	27.88	28.72	31.17	35.21	41.07	48.86	58.49	69.51	81.10	92.23	95.66
7.625	32.09	33.49	34.46	37.27	41.69	47.73	55.31	64.19	73.90	83.76	93.04	96.25
9.000	38.16	39.65	40.64	43.53	47.94	53.77	60.84	68.84	77.35	85.81	93.66	96.69
10.375	44.35	45.81	46.77	49.55	53.74	59.16	65.59	72.71	80.15	87.45	94.16	96.87
11.875	50.82	52.19	53.07	55.63	59.45	64.32	70.02	76.25	82.67	88.90	94.60	97.17
14.375	60.38	61.53	62.26	64.38	67.52	71.47	76.04	80.96	85.97	90.80	95.19	97.17
16.875	68.23	69.15	69.74	71.44	73.95	77.09	80.69	84.56	88.47	92.22	95.63	97.17
18.125	71.55	72.37	72.89	74.41	76.63	79.42	82.62	86.04	89.49	92.81	95.81	97.17
24.375	83.32	83.77	84.05	84.88	86.09	87.61	89.34	91.18	93.05	94.83	96.44	97.17
30.750	89.80	90.04	90.19	90.63	91.28	92.08	93.00	93.99	94.98	95.92	96.78	97.17
36.875	93.15	93.28	93.36	93.60	93.95	94.39	94.90	95.43	95.97	96.49	96.95	97.17

43.125	95.00	95.07	95.12	95.25	95.44	95.67	95.94	96.23	96.52	96.80	97.05	97.17
49.375	96.00	96.04	96.06	96.13	96.24	96.36	96.51	96.66	96.82	96.97	97.11	97.17
55.625	96.54	96.56	96.57	96.61	96.67	96.73	96.81	96.90	96.98	97.06	97.13	97.17
61.875	96.83	96.84	96.85	96.87	96.90	96.93	96.98	97.02	97.07	97.11	97.15	97.17
68.125	96.98	96.99	96.99	97.01	97.02	97.04	97.06	97.09	97.11	97.14	97.16	97.17
74.375	97.07	97.07	97.07	97.08	97.09	97.10	97.11	97.12	97.14	97.15	97.16	97.17
80.625	97.11	97.12	97.12	97.12	97.12	97.13	97.14	97.14	97.15	97.16	97.16	97.17
86.875	97.14	97.14	97.14	97.14	97.14	97.15	97.15	97.15	97.16	97.16	97.17	97.17
99.375	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.17	97.17	97.17
105.620	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.16	97.17	97.17	97.17	97.17
111.870	97.16	97.16	97.16	97.16	97.16	97.16	97.17	97.17	97.17	97.17	97.17	97.17
118.120	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
124.380	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
130.630	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
136.880	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
143.130	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
149.370	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
155.630	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
161.880	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
168.130	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
174.380	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
180.620	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
186.880	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
193.130	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
199.380	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
205.630	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
211.880	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
224.380	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
230.630	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
236.880	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17
249.380	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17	97.17

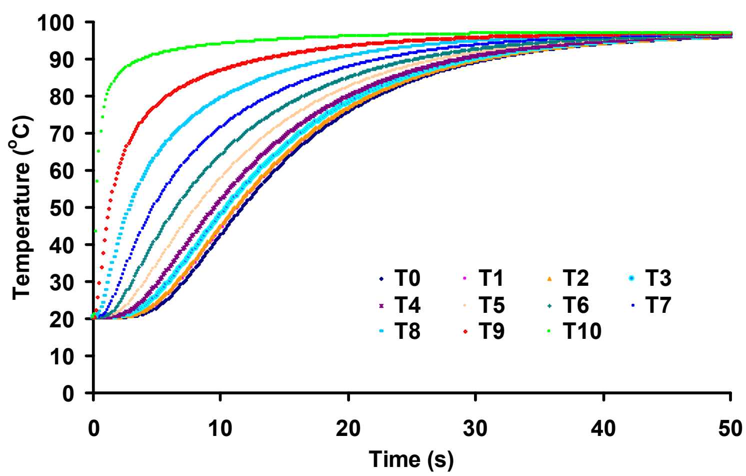

Figure C7. Simulated cooking curve for soaked kabuli chickpea at 98.7°C.

Table C8. Temperature distribution of unsoaked chickpea at 98°C.

Time	Temperature (°C)											
(s)	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	TS
0.000	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	68.10
0.125	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	26.22	72.29
0.250	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.82	26.53	42.85	75.48
0.375	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.81	25.94	28.22	53.88	77.61
0.500	25.80	25.80	25.80	25.80	25.80	25.80	25.80	25.83	26.20	30.39	61.60	87.60
0.625	25.80	25.80	25.80	25.80	25.80	25.80	25.81	25.87	26.60	32.80	67.23	93.01
0.750	25.80	25.80	25.80	25.80	25.80	25.80	25.81	25.95	27.14	35.27	71.42	93.83
0.875	25.80	25.80	25.80	25.80	25.80	25.80	25.83	26.06	27.81	37.73	74.61	94.47
1.000	25.80	25.80	25.80	25.80	25.80	25.81	25.85	26.22	28.59	40.10	77.07	94.99
2.375	25.80	25.80	25.81	25.82	25.89	26.17	27.23	30.62	39.65	58.51	87.06	95.46
6.250	26.44	26.75	27.06	27.99	29.92	33.48	39.53	48.80	61.47	76.69	92.47	95.68
7.625	27.52	28.10	28.60	30.09	32.85	37.41	44.34	53.95	66.05	79.68	93.29	96.19
9.000	29.29	30.15	30.82	32.80	36.22	41.46	48.83	58.38	69.73	82.00	93.93	96.42
10.375	31.69	32.78	33.59	35.94	39.82	45.45	52.95	62.21	72.78	83.86	94.45	97.27
11.875	34.88	36.15	37.05	39.66	43.83	49.63	57.04	65.84	75.57	85.53	94.92	97.85
14.375	40.95	42.37	43.33	46.10	50.37	56.05	62.98	70.89	79.33	87.75	95.56	98.24
16.875	47.33	48.75	49.68	52.37	56.44	61.73	68.02	75.01	82.31	89.48	96.07	98.51
18.125	50.46	51.84	52.75	55.35	59.27	64.31	70.25	76.80	83.59	90.22	96.30	98.60
24.375	64.35	65.44	66.13	68.13	71.09	74.83	79.13	83.77	88.49	93.03	97.15	98.73
30.750	74.90	75.68	76.17	77.60	79.69	82.32	85.33	88.54	91.80	94.91	97.73	98.82
36.875	82.10	82.65	83.00	84.00	85.48	87.33	89.44	91.70	93.97	96.15	98.12	98.89
43.125	87.25	87.64	87.88	88.58	89.61	90.90	92.36	93.93	95.51	97.02	98.39	98.93
49.375	90.84	91.11	91.28	91.77	92.48	93.37	94.39	95.48	96.58	97.63	98.57	98.96
55.625	93.34	93.52	93.64	93.98	94.47	95.09	95.80	96.56	97.32	98.05	98.70	98.98
61.875	95.07	95.20	95.28	95.51	95.86	96.29	96.78	97.30	97.83	98.34	98.79	99.00
68.125	96.27	96.36	96.42	96.58	96.82	97.12	97.46	97.82	98.19	98.54	98.86	99.00
74.375	97.10	97.17	97.21	97.32	97.49	97.69	97.93	98.18	98.44	98.68	98.90	99.00
80.625	97.68	97.73	97.75	97.83	97.95	98.09	98.26	98.43	98.61	98.78	98.93	99.00
86.875	98.09	98.12	98.14	98.19	98.27	98.37	98.48	98.61	98.73	98.85	98.95	99.00
99.375	98.56	98.57	98.58	98.61	98.65	98.70	98.75	98.81	98.87	98.93	98.98	99.00
105.620	98.69	98.70	98.71	98.73	98.76	98.79	98.83	98.87	98.91	98.95	98.98	99.00
111.870	98.79	98.80	98.80	98.81	98.83	98.85	98.88	98.91	98.94	98.96	98.99	99.00
118.120	98.85	98.86	98.86	98.87	98.88	98.90	98.92	98.94	98.96	98.98	98.99	99.00
124.380	98.90	98.90	98.90	98.91	98.92	98.93	98.94	98.96	98.97	98.98	99.00	99.00
130.630	98.93	98.93	98.93	98.94	98.94	98.95	98.96	98.97	98.98	98.99	99.00	99.00
136.880	98.95	98.95	98.95	98.96	98.96	98.97	98.97	98.98	98.99	98.99	99.00	99.00
143.130	98.97	98.97	98.97	98.97	98.97	98.98	98.98	98.99	98.99	98.99	99.00	99.00
149.370	98.98	98.98	98.98	98.98	98.98	98.98	98.99	98.99	98.99	99.00	99.00	99.00
155.630	98.98	98.98	98.98	98.99	98.99	98.99	98.99	98.99	99.00	99.00	99.00	99.00
161.880	98.99	98.99	98.99	98.99	98.99	98.99	98.99	99.00	99.00	99.00	99.00	99.00
168.130	98.99	98.99	98.99	98.99	98.99	98.99	99.00	99.00	99.00	99.00	99.00	99.00
174.380	98.99	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
180.620	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
186.880	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
193.130	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
199.380	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
205.630	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
211.880	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00

224.380	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
230.630	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
236.880	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00
249.380	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00	99.00

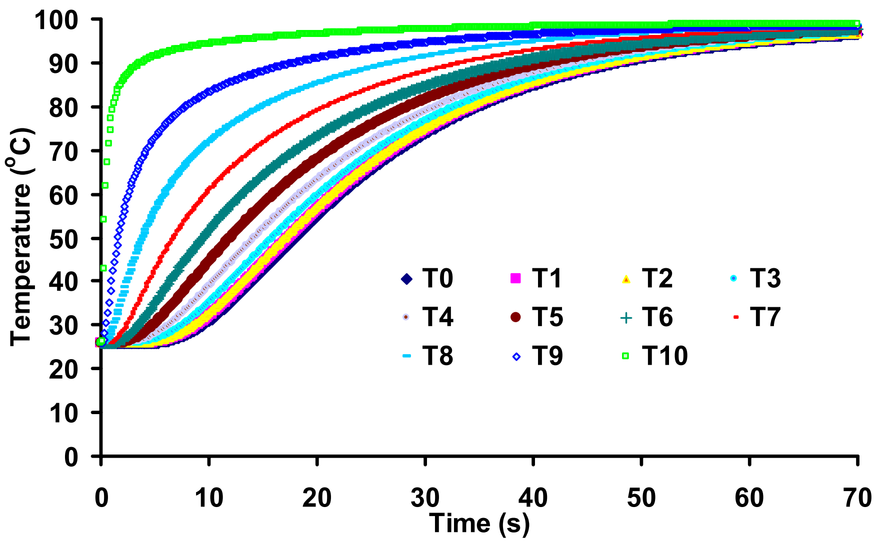

Figure C8. Simulated cooking curve for unsoaked kabuli chickpea at 98.7°C.

APPENDIX D

Deviations of the Simulated from the Experimental Moisture and Temperature Profiles.

Table D1. Deviation of simulated temperature from experimental temperatures during cooking of unsoaked chickpea.

Time	Set Point Temperature (°C)			
(s)	70	80	90	98
0.000	0.0000	0.0000	0.0000	-0.0400
0.125	0.0500	0.0000	0.0000	-0.0400
0.250	0.0000	0.0000	0.0000	-0.0400
0.375	0.0500	0.0000	0.0500	0.0900
0.500	0.0000	-0.0500	0.0000	-0.0400
0.625	0.0000	0.0000	0.0500	-0.0400
0.750	0.0000	-0.0500	0.0000	-0.0400
0.875	0.0000	-0.0500	0.0500	-0.0400
1.000	0.0000	-0.0500	0.0000	-0.0900
1.125	0.0000	-0.0500	0.0500	-0.0400
1.250	0.0000	-0.0500	0.0500	-0.0400
1.375	0.0000	-0.0500	0.1000	-0.0400
1.500	0.0000	-0.1000	0.0500	-0.0400
1.625	0.0000	-0.1000	0.1000	-0.0900
1.750	0.0000	-0.1000	0.0500	-0.0410
1.875	0.0000	-0.1000	0.1000	-0.0410
2.000	0.0000	-0.1500	0.1000	-0.0410
2.125	0.0000	-0.1500	0.1000	-0.0420
2.250	0.0000	-0.1500	0.1000	-0.0930
2.375	0.0000	-0.1500	0.1000	-0.0450
2.500	0.0000	-0.1500	0.0990	0.0720
2.625	0.0000	-0.1500	0.1390	-0.0800
2.750	0.0000	-0.1500	0.1390	-0.0890
2.875	0.0000	-0.2000	0.1380	-0.0980
3.000	0.0000	-0.2000	0.1380	-0.1090
3.125	0.0000	-0.2000	0.1370	-0.1210
3.250	0.0000	-0.2000	0.1360	-0.1350
3.375	0.0000	-0.2010	0.1350	-0.1500
3.500	0.0000	-0.2510	0.1340	-0.1670
3.625	0.0000	-0.2510	0.1330	-0.1870
3.750	-0.0010	-0.2010	0.1310	-0.1340
3.875	-0.0010	-0.2520	0.1280	0.1530
4.000	-0.0010	-0.2520	0.1260	0.1760
4.125	-0.0010	-0.2530	0.1730	0.2510
4.250	-0.0010	-0.2940	0.1690	0.2300
4.375	-0.0020	-0.2940	0.1650	-0.2220
4.500	-0.0020	-0.2950	0.1610	-0.1580
4.625	-0.0020	-0.2970	0.1550	-0.0580
4.750	-0.0030	-0.3480	0.1490	0.1380
4.875	-0.0030	-0.3500	0.1430	0.4790

5.000	-0.0040	-0.3520	0.1350	0.7560
5.125	-0.0050	-0.3540	0.1770	1.1790
5.250	-0.0060	-0.3560	0.1170	1.6460
5.375	-0.0060	-0.3590	0.1570	-2.1480
5.500	-0.0080	-0.4120	0.1460	2.5560
5.625	-0.0090	-0.4160	0.1330	2.7580
5.750	-0.0100	-0.4200	0.1200	-3.0140
5.875	-0.0110	-0.5650	0.1050	2.9650
6.000	-0.0130	-0.5700	0.0890	3.3010
6.125	-0.0150	-0.5750	0.0710	-3.2510
6.250	-0.0170	-0.6320	0.0520	3.4250
6.375	-0.0190	-0.6380	0.0820	3.4630
6.500	-0.0220	-0.6460	0.0100	3.5750
6.625	-0.0240	-0.6540	-0.0140	-3.6420
6.750	-0.0270	-0.7130	-0.0390	-3.8030
6.875	-0.0300	-0.7230	-0.0660	-3.8580
7.000	-0.0340	-0.7340	-0.0940	-4.0470
7.125	-0.0380	-0.7450	-0.1250	-4.0400
7.250	-0.0420	-0.7580	-0.1570	-4.2180
7.375	-0.0460	-0.7710	-0.1910	4.3000
7.500	-0.0910	0.1150	0.8230	4.4660
7.625	-0.0560	0.0990	-0.4150	4.5360
7.750	-0.0610	0.0830	-0.4050	-4.6410
7.875	-0.0670	0.0650	-0.1160	-4.7500
8.000	-0.0730	0.0470	0.1300	-4.7940
8.125	-0.0800	0.0270	0.3740	4.7020
8.250	-0.1270	0.0060	0.5650	4.9250
8.375	-0.0940	-0.0170	-0.3450	4.9630
8.500	-0.1020	-0.0400	0.5530	4.9860
8.625	-0.1110	-0.0650	-0.1220	5.0140
8.750	-0.1200	-0.0920	0.1110	5.0260
8.875	-0.1290	-0.1190	0.2920	-5.0440
9.000	-0.1790	-0.1480	0.4710	-5.0480
9.125	-0.1500	-0.1790	0.5470	5.0070
9.250	-0.2010	-0.2110	0.7210	5.0010
9.375	-0.2120	-0.2440	0.7930	5.0010
9.500	-0.1340	-0.2790	0.8730	5.0370
9.625	-0.0970	-0.3160	0.9900	-5.0290
9.750	0.0300	-0.3540	0.5250	-5.0060
9.875	0.1660	-0.3940	0.1180	-5.0300
10.000	0.1510	-0.4350	0.2790	5.0510

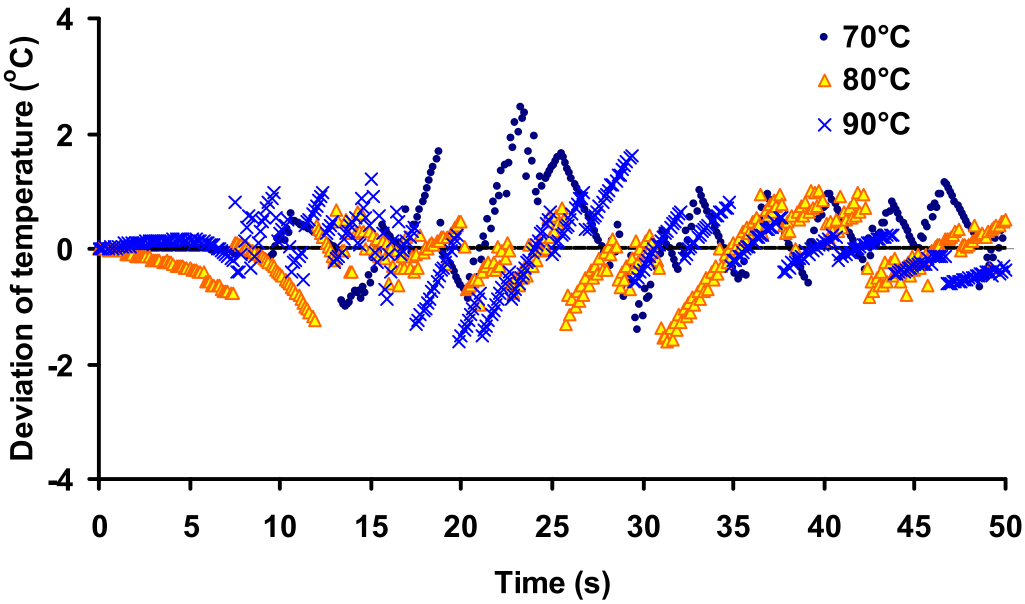

Figure D1. Deviation of simulated temperature from experimental temperatures during cooking of unsoaked chickpea.

Table D2. Deviation of simulated temperature from experimental temperatures during cooking of soaked chickpea.

Time	Set Point Temperature (°C)			
(s)	70	80	90	98
0.000	0.0000	0.0000	0.0000	-0.3700
0.125	0.0000	0.0000	0.0000	-0.2200
0.250	0.0000	0.0000	0.0000	-0.1200
0.375	0.0000	0.0000	0.0000	-0.0300
0.500	0.0000	0.0000	0.0000	0.0700
0.625	0.0000	0.0000	0.0000	0.1700
0.750	0.0000	0.0000	0.0000	0.3100
0.875	0.0000	0.0000	0.0000	-0.3700
1.000	0.0000	0.0000	0.0000	-0.2200
1.125	0.0000	0.0000	-0.0500	-0.1200
1.250	1.1100	0.0000	-0.0500	-0.0300
1.375	1.1100	0.0000	0.4800	0.0700
1.500	1.1100	-0.0010	0.2390	0.1690
1.625	1.1600	-0.0010	0.6290	0.3080
1.750	1.1090	-0.0020	0.3770	0.4070
1.875	1.1090	-0.0040	0.8650	0.5550
2.000	1.1080	0.0440	0.5720	0.5910
2.125	1.1070	0.0400	0.9980	0.6850
2.250	1.1050	-0.0160	0.7510	0.7270
2.375	1.1020	-0.0240	1.1810	0.8660

2.500	1.0990	-0.0350	0.9180	0.8000
2.625	1.0940	0.0000	1.3400	0.9690
2.750	1.0870	0.0310	1.0780	1.0930
2.875	1.0780	0.1070	1.4790	1.3490
3.000	1.0680	0.1270	1.2030	1.1680
3.125	1.0540	0.1910	1.6000	1.4470
3.250	1.0370	0.1870	1.0180	1.2960
3.375	1.0170	0.2350	-0.4040	1.4140
3.500	0.9930	0.2240	0.4930	1.2290
3.625	0.9650	0.2930	-0.4610	1.3320
3.750	0.9320	0.3120	0.5530	0.2000
3.875	0.8930	0.4100	0.6850	-0.6050
4.000	0.8500	0.4070	-0.2070	-0.3570
4.125	0.8010	0.4420	0.9570	-0.2240
4.250	0.7450	0.8950	-1.6630	-0.0570
4.375	0.6840	0.4650	0.6930	-0.0970
4.500	0.5650	0.3630	1.3330	-0.0140
4.625	0.5400	0.4380	-1.2710	0.6320
4.750	0.4080	0.3100	0.0200	0.6320
4.875	0.3690	0.4080	0.4150	0.4240
5.000	0.2220	0.2450	1.0960	0.3390
5.125	0.1180	0.3180	0.2120	0.4770
5.250	-0.0430	0.0880	0.8130	0.4590
5.375	-0.1120	0.1860	-1.8800	0.8540
5.500	-0.2880	-0.0680	0.4230	0.6140
5.625	-0.4210	0.0070	-0.4580	0.3480
5.750	-0.5620	0.3990	0.2680	0.6980
5.875	-0.7100	0.0600	0.8000	0.5130
6.000	-0.8650	0.1510	-0.1290	0.1540
6.125	-1.0270	-0.2090	0.3290	0.6010
6.250	-1.1960	-0.1890	0.7660	0.1760
6.375	-1.3710	-0.6180	-0.3380	-0.0710
6.500	-1.5540	-0.5270	0.3280	-0.4700
6.625	-1.7420	-0.0040	2.3140	-0.2100
6.750	-1.9360	-0.5100	1.2800	-0.6800
6.875	-2.0370	-0.2930	1.6680	-0.9210
7.000	-1.7130	-0.3340	0.6170	-1.3600
7.125	-1.2140	-0.9510	1.1280	-1.0980
7.250	-0.8510	-0.8050	2.1520	-1.4140
7.375	-0.3630	-1.3850	2.5990	-0.5480
7.500	0.1310	-1.2500	-0.0400	-0.8780
7.625	0.5700	-0.9910	2.5750	-1.3040
7.750	0.9450	-0.8660	0.8250	-0.8470
7.875	1.1850	-1.5160	1.3000	-1.1440
8.000	1.4120	-1.4000	0.1610	-0.9770
8.125	1.4050	-2.0070	0.6680	-1.2430
8.250	1.4840	-1.9070	0.9410	-0.9840
8.375	1.4710	-2.6200	1.0610	-1.2070
8.500	1.4940	-1.5160	-0.0410	-0.9640
8.625	1.4250	-1.6140	0.9240	-1.1930

8.750	-1.4530	-0.1530	1.4070	-1.7130
8.875	-1.3790	-1.4340	0.3480	-1.5160
9.000	-1.3930	-0.6370	0.4090	-2.0400
9.125	-1.2650	-1.3000	-0.0920	-1.1440
9.250	-1.6550	-0.0440	-1.1530	-1.3390
9.375	-1.1930	0.2320	-1.0950	-1.8540
9.500	-1.2500	0.5470	-0.7070	-1.6290
9.625	-1.1160	-0.3970	-0.4580	-1.8140
9.750	-1.1300	0.0190	-0.2090	-1.5380
9.875	-0.9940	-0.3750	-1.0790	-2.0610
10.000	-0.9970	0.2730	-0.3190	-1.3630

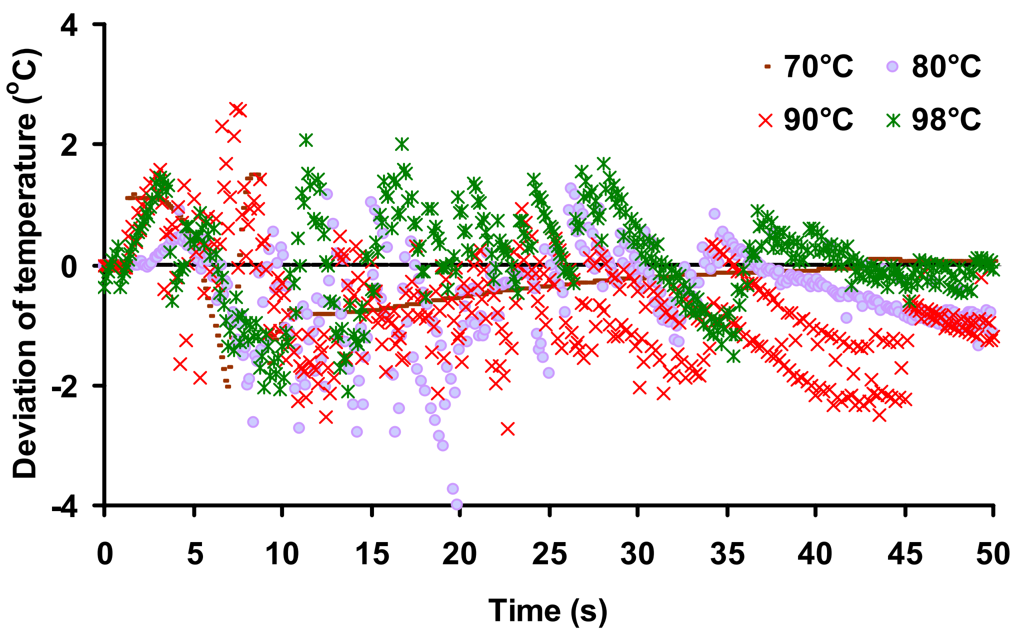

Figure D2. Deviation of simulated temperature from experimental temperatures during cooking of soaked chickpea.

Table D3. Deviation of simulated and experimental moisture ratio during cooking of unsoaked chickpea.

Time	Set Point Moisture Ratio			
h	70°C	80°C	90°C	98°C
0	0.00	0.00	0.00	0.00
1	-0.01	-0.07	-0.02	-0.14
2	-0.05	-0.04	0.01	0.04
3	0.01	-0.01	0.09	-0.01
4	-0.02	0.04	0.04	-0.06
5	0.00	0.05	0.01	0.00
6	0.03	0.02	-0.05	
7	-0.03	-0.04	-0.02	
8	-0.02	-0.12	-0.01	
9	-0.01	-0.08	-0.01	
10	0.00	-0.06	0.00	
11	-0.10	-0.04		
12	0.00	0.00		

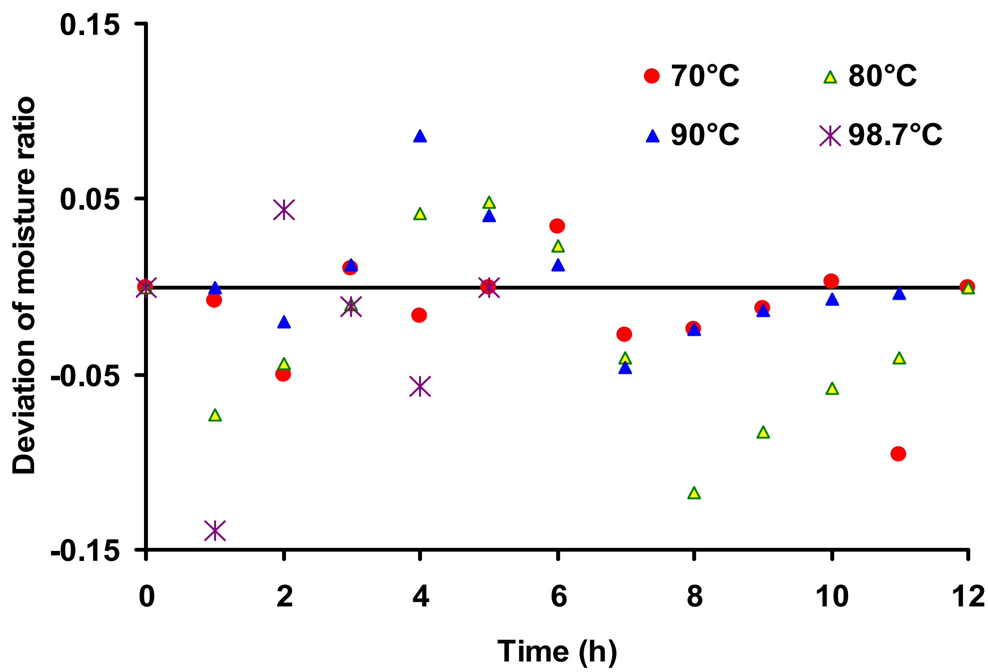

Figure D3. Deviation of simulated moisture ratio from experimental moisture ratio changes during cooking of unsoaked chickpea.

Table D4: Deviation of simulated and experimental moisture ratio during cooking of soaked chickpea.

Time	Set Point Moisture Ratio			
h	70°C	80°C	90°C	98°C
0	0.00	0.00	0.00	0.00
1	-0.01	-0.08	0.09	0.04
2	0.01	-0.10	0.08	0.00
3	0.06	0.03	0.02	-0.01
4	-0.01	0.01	-0.01	0.00
5	0.00	-0.01		
6	0.03	-0.04		
7	-0.01	-0.04		
8	-0.03	-0.02		
9	-0.09	-0.01		
10	-0.06	0.00		
11	-0.04			
12	0.00			

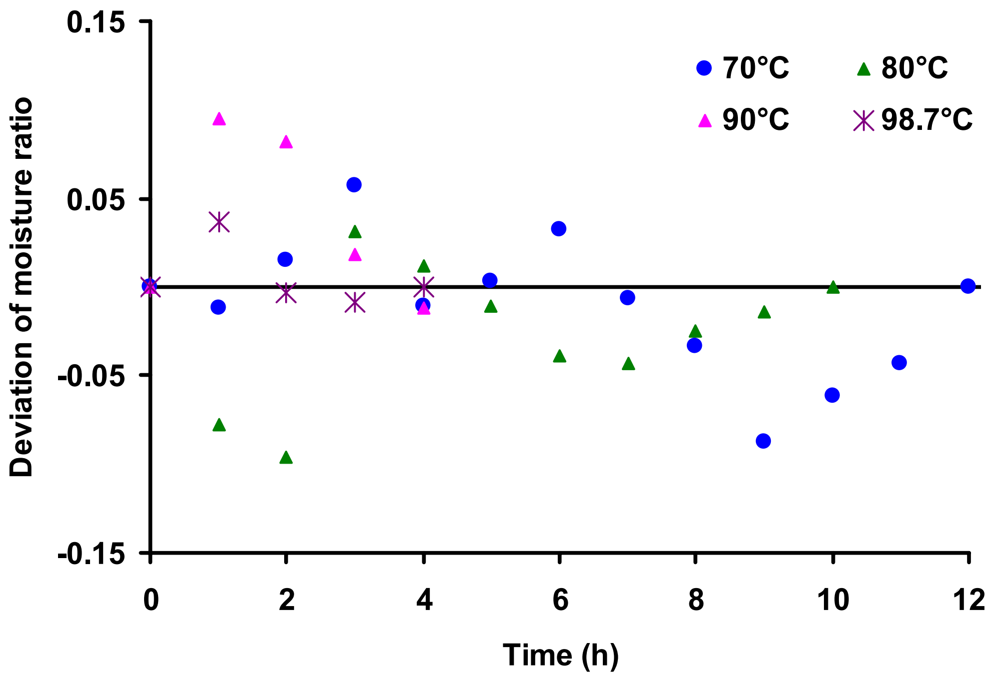

Figure D4. Deviation of simulated moisture ratio from experimental moisture ratio changes during cooking of soaked chickpea.

APPENDIX E

Experimental and Simulated Results.

Table E1. Experimental and simulated temperatures during cooking of unsoaked kabuli chickpea.

	70°C		80°C		90°C		98°C	
Time (s)	Exp (°C)	Sim (°C)	Exp (°C)	Sim (°C)	Exp (°C)	Sim (°C)	Exp (°C)	Sim (°C)
0.000	24.84	24.84	23.87	23.87	26.51	26.51	25.76	25.80
0.125	24.89	24.84	23.87	23.87	26.51	26.51	25.76	25.80
0.250	24.84	24.84	23.87	23.87	26.51	26.51	25.76	25.80
0.375	24.89	24.84	23.87	23.87	26.56	26.51	25.71	25.80
0.500	24.84	24.84	23.82	23.87	26.51	26.51	25.76	25.80
0.625	24.84	24.84	23.87	23.87	26.56	26.51	25.76	25.80
1.000	24.84	24.84	23.82	23.87	26.51	26.51	25.71	25.80
3.500	24.84	24.84	23.62	23.87	26.65	26.52	25.70	25.86
6.000	24.84	24.85	23.34	23.91	26.75	26.66	30.15	26.85
8.500	24.84	24.94	24.14	24.18	27.89	27.34	34.93	29.94
11.000	25.66	25.22	24.14	24.96	28.71	28.86	39.94	34.99
13.500	24.80	25.78	26.36	26.40	31.42	31.24	45.69	41.10
16.000	26.91	26.66	27.85	28.45	34.21	34.31	51.64	47.48
18.000	29.27	27.85	31.04	30.96	37.12	37.79	57.07	53.64
24.250	32.24	31.43	37.69	37.60	46.45	46.33	67.47	65.90
30.500	35.31	35.95	44.94	44.85	54.94	55.01	75.70	75.84
36.625	41.06	40.37	51.45	51.18	62.48	62.24	81.40	82.76
43.000	44.81	44.59	56.07	56.73	68.51	68.33	86.30	87.80
49.250	48.21	48.23	61.50	61.17	72.60	73.07	89.90	91.22
55.500	51.41	51.36	64.13	64.76	76.70	76.81	92.60	93.60
61.750	53.18	54.02	67.85	67.64	80.00	79.74	94.50	95.25
68.000	56.39	56.26	70.40	69.95	82.50	82.03	95.90	96.40
74.250	59.23	58.14	72.60	71.79	84.30	83.82	97.00	97.19
80.500	59.90	59.72	74.20	73.27	85.70	85.22	97.80	97.75
86.750	61.37	61.04	75.20	74.45	86.70	86.31	98.40	98.13
93.000	63.02	62.14	75.80	75.39	87.40	87.16	98.80	98.40
99.250	63.25	63.06	76.80	76.14	88.00	87.83	98.90	98.58
105.500	64.09	63.83	77.30	76.73	88.40	88.35	98.90	98.71
111.750	64.67	64.47	77.50	77.21	88.70	88.75	98.90	98.80
117.750	65.47	64.99	77.80	77.58	89.00	89.06	98.90	98.86
124.250	66.04	65.45	78.00	77.90	89.30	89.32	98.90	98.90
130.500	66.44	65.83	78.20	78.14	89.50	89.51	98.90	98.93
136.750	66.71	66.14	77.90	78.33	89.60	89.66	98.90	98.95
143.000	66.88	66.40	77.90	78.49	89.70	89.78	98.90	98.97
149.250	67.10	66.62	78.50	78.61	89.80	89.87	98.90	98.98
155.500	67.54	66.80	78.50	78.71	89.90	89.94	98.90	98.98
161.750	67.37	66.95	78.50	78.79	90.00	90.00	98.90	98.99
168.000	67.19	67.07	78.60	78.85	90.00	90.04	98.90	98.99
174.250	66.97	67.18	78.50	78.90	90.00	90.08	98.93	99.00
180.500	66.88	67.27	78.60	78.94	90.00	90.11	98.93	99.00
186.750	66.92	67.34	78.60	78.97	90.00	90.13	98.93	99.00

Table E2: Experimental and simulated temperatures during cooking of soaked kabuli chickpea.

Time (s)	70°C Exp (°C)	70°C Sim (°C)	80°C Exp (°C)	80°C Sim (°C)	90°C Exp (°C)	90°C Sim (°C)	98°C Exp (°C)	98°C Sim (°C)
0.000	20.84	20.84	20.61	20.61	20.54	20.54	20.12	20.49
0.125	20.84	20.84	20.61	20.61	20.54	20.54	20.27	20.49
0.250	20.84	20.84	20.61	20.61	20.54	20.54	20.37	20.49
0.375	20.84	20.84	20.61	20.61	20.54	20.54	20.46	20.49
0.500	20.84	20.84	20.61	20.61	20.54	20.54	20.56	20.49
0.625	20.84	20.84	20.61	20.61	20.54	20.54	20.66	20.49
0.750	20.84	20.84	20.61	20.61	20.54	20.54	20.80	20.49
0.875	20.84	20.84	20.61	20.61	20.54	20.54	20.12	20.49
1.000	20.84	20.84	20.61	20.61	20.54	20.54	20.27	20.49
3.500	21.95	20.96	21.15	20.93	21.41	20.92	22.16	20.93
6.000	21.85	22.72	24.77	24.62	25.12	25.25	26.06	25.91
8.500	28.52	27.03	30.70	32.22	34.03	34.07	34.95	35.91
11.000	33.70	32.89	38.10	40.82	42.31	44.01	47.08	47.10
13.500	39.24	38.42	48.79	48.69	53.22	53.05	55.69	57.23
16.000	44.35	43.62	55.57	55.29	59.67	60.62	66.81	65.67
18.000	47.93	47.29	59.17	59.65	65.07	65.61	71.10	71.23
24.250	56.16	55.77	68.62	69.04	76.20	76.34	84.40	83.15
30.500	61.03	60.80	74.70	74.16	81.50	82.19	89.70	89.61
36.500	63.77	63.63	77.00	76.85	84.00	85.27	93.20	93.00
43.000	65.49	65.41	77.90	78.44	84.80	87.08	94.80	94.98
49.250	66.43	66.38	77.90	79.25	87.10	88.01	96.00	95.99
55.500	67.15	66.95	78.50	79.68	87.30	88.51	96.10	96.53
61.750	66.97	67.27	78.80	79.92	87.50	88.78	96.10	96.82
68.000	67.15	67.46	79.00	80.05	87.60	88.93	96.40	96.98
74.250	67.06	67.57	79.10	80.12	87.90	89.01	96.70	97.07
80.500	67.32	67.63	79.20	80.16	87.90	89.05	96.50	97.11
86.750	67.45	67.67	78.90	80.18	88.00	89.07	96.50	97.14
93.000	67.50	67.69	79.00	80.19	88.10	89.09	96.10	97.15
99.250	67.63	67.70	78.90	80.19	87.90	89.09	96.70	97.16
105.500	67.67	67.71	79.10	80.20	88.20	89.10	96.40	97.16
111.750	67.89	67.71	80.00	80.20	88.20	89.10	96.30	97.16
117.625	67.45	67.71	79.00	80.20	88.60	89.10	97.20	97.17
124.250	67.72	67.71	80.00	80.20	88.10	89.10	96.30	97.17
130.500	67.41	67.71	80.00	80.20	88.00	89.10	96.70	97.17
136.750	67.14	67.71	79.90	80.20	87.50	89.10	96.40	97.17
143.000	66.97	67.71	80.00	80.20	88.90	89.10	95.90	97.17
149.250	66.92	67.71	79.00	80.20	88.60	89.10	96.50	97.17
155.500	67.06	67.71	79.00	80.20	89.10	89.10	96.10	97.17
161.750	66.92	67.71	79.90	80.20	88.80	89.10	96.70	97.17
168.000	66.92	67.71	79.30	80.20	88.50	89.10	95.60	97.17
174.250	67.15	67.71	80.10	80.20	88.40	89.10	96.20	97.17
180.500	67.37	67.71	80.00	80.20	87.80	89.10	95.90	97.17
186.750	67.50	67.71	79.70	80.20	87.80	89.10	96.10	97.17
193.000	67.58	67.71	79.20	80.20	87.50	89.10	96.10	97.17

Table E3: Experimental and simulated moisture ratio during cooking of unsoaked kabuli chickpea.

	70°C		80°C		90°C		98.7°C	
Time (h)	Exp MR	Sim MR	Exp MR	Sim MR	Exp MR	Sim MR	Exp MR	Sim MR
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	0.99	1.00	0.92	0.99	0.89	0.91	0.63	0.77
2	0.89	0.94	0.83	0.87	0.57	0.56	0.38	0.34
3	0.81	0.80	0.65	0.66	0.39	0.30	0.13	0.14
4	0.62	0.64	0.52	0.48	0.20	0.16	0.00	0.06
5	0.50	0.50	0.39	0.34	0.10	0.09	0.00	0.00
6	0.41	0.38	0.26	0.24	0.00	0.05		
7	0.26	0.29	0.13	0.17	0.00	0.02		
8	0.20	0.22	0.00	0.12	0.00	0.01		
9	0.15	0.17	0.00	0.08	0.00	0.01		
10	0.13	0.13	0.00	0.06	0.00	0.00		
11	0.00	0.10	0.00	0.04				

Table E4: Experimental vs simulated moisture ratio during cooking of soaked kabuli chickpea.

	70°C		80°C		90°C		98°C	
Time (h)	Exp MR	Sim MR	Exp MR	Sim MR	Exp MR	Sim MR	Exp MR	Sim MR
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	0.98	0.99	0.87	0.94	0.58	0.49	0.37	0.33
2	0.89	0.88	0.55	0.64	0.20	0.12	0.05	0.06
3	0.73	0.67	0.42	0.38	0.05	0.03	0.00	0.01
4	0.48	0.49	0.24	0.22	0.00	0.01	0.00	0.00
5	0.35	0.35	0.12	0.13	0.00	0.00		
6	0.28	0.25	0.04	0.07				
7	0.17	0.17	0.00	0.04				
8	0.09	0.12	0.00	0.02				
9	0.00	0.09	0.00	0.01				
10	0.00	0.06	0.00	0.00				
11	0.00	0.04						

APPENDIX F

Experimental Values Shown in Replicates.

Table F1. Moisture content of chickpea seed samples used in experiments.

Level	Replicate	MC (% w.b.)	Mean (% w.b.)	SD (% w.b.)	CV (%)
1	1	9.69			
	2	9.97			
	3	9.93	9.86	0.15	1.55
2	1	13.49			
	2	13.13			
	3	12.99	13.20	0.26	1.98
3	1	18.15			
	2	18.16			
	3	18.20	18.17	0.02	0.13
4	1	26.60			
	2	26.52			
	3	26.49	26.54	0.05	0.22
5	1	37.74			
	2	37.94			
	3	37.99	37.89	0.13	0.35
6	1	56.17			
	2	56.15			
	3	55.58	55.97	0.33	0.60
7	1	65.48			
	2	64.88			
	3	65.35	65.24	0.31	0.48

Table F2. Particle density of chickpea as a function of moisture content.

Moisture content (% w.b.)	Trial	Density (kg/m^3)	Mean (kg/m^3)	SD (kg/m^3)	CV (%)
9.86	1	1445.41			
9.86	2	1465.53			
9.86	3	1437.34			
9.86	4	1462.60			
9.86	5	1486.32	1459.44	19.07	1.31
13.20	1	1392.80			
13.20	2	1360.50			
13.20	3	1395.38			
13.20	4	1415.28			
13.20	5	1411.33	1395.06	21.63	1.55
18.17	1	1369.91			
18.17	2	1408.75			
18.17	3	1388.63			
18.17	4	1397.26			
18.17	5	1356.34	1384.18	21.05	1.52
25.10	1	1363.80			
25.10	2	1334.30			
25.10	3	1341.57			
25.10	4	1344.06			
25.10	5	1342.26	1345.20	11.04	0.82
35.89	1	1298.98			
35.89	2	1321.12			
35.89	3	1299.97			
35.89	4	1306.50			
35.89	5	1301.00	1305.51	9.19	0.70
55.97	1	1207.76			
55.97	2	1190.83			
55.97	3	1211.27			
55.97	4	1191.18			
55.97	5	1209.52	1202.11	10.21	0.85
65.24	1	1108.37			
65.24	2	1107.64			
65.24	3	1109.51			
65.24	4	1115.70			
65.24	5	1107.87	1109.82	3.36	0.30

Table F3. Determination of thermal conductivity using the assembled probe

Temp (°C)	Moisture content (% w.b.)	k (W/m °C) Trial 1	Trial 2	Trial 3	Mean	SD*	CV (%)	k model (W/m °C)
25	7.00	0.1533	0.1542	0.1531	0.1535	0.00060	0.39	0.1633
25	9.86	0.1799	0.1863	0.1886	0.1849	0.00450	2.44	0.1795
25	13.20	0.2172	0.2154	0.2162	0.2163	0.00090	0.42	0.1985
25	18.17	0.2386	0.2351	0.2359	0.2365	0.00183	0.78	0.2268
25	25.10	0.2443	0.2466	0.2458	0.2456	0.00116	0.48	0.2662
40	7.00	0.1695	0.1695	0.1694	0.1694	0.00003	0.02	0.1757
40	9.86	0.1975	0.1981	0.1943	0.1966	0.00204	1.04	0.1920
40	13.20	0.2287	0.2296	0.2298	0.2294	0.00058	0.26	0.2110
40	18.17	0.2487	0.2484	0.2502	0.2491	0.00096	0.39	0.2392
40	25.10	0.2642	0.2636	0.2634	0.2637	0.00041	0.16	0.2787
60	7.00	0.1789	0.1795	0.1800	0.1795	0.00053	0.30	0.1923
60	9.86	0.2022	0.2035	0.2029	0.2029	0.00065	0.32	0.2086
60	13.20	0.2402	0.2392	0.2384	0.2393	0.00090	0.38	0.2276
60	18.17	0.2597	0.2665	0.2634	0.2632	0.00340	1.29	0.2558
60	25.10	0.2854	0.2866	0.2868	0.2863	0.00075	0.26	0.2952
80	7.00	0.1878	0.1897	0.1883	0.1886	0.00097	0.52	0.2089
80	9.86	0.2122	0.2146	0.2127	0.2132	0.00126	0.59	0.2252
80	13.20	0.2534	0.2531	0.2523	0.2529	0.00056	0.22	0.2442
80	18.17	0.2812	0.2799	0.2801	0.2804	0.00070	0.25	0.2724
80	25.10	0.2998	0.2976	0.3029	0.3001	0.00266	0.89	0.3118
98	7.00	0.2164	0.2122	0.2123	0.2137	0.00237	1.11	0.2255
98	9.86	0.2363	0.2337	0.2329	0.2343	0.00177	0.76	0.2417
98	13.20	0.2837	0.2860	0.2828	0.2842	0.00165	0.58	0.2607
98	18.17	0.3093	0.3098	0.3082	0.3091	0.00081	0.26	0.2890
98	25.10	0.3263	0.3255	0.3254	0.3257	0.00047	0.15	0.3284

* Standard Deviation (n=3); CV- Coefficient of variation.

Table F4. Heat capacity of assembled calorimeter.

	Trial			Mean	SD	CV
	1	2	3			(%)
m_w (kg)	2.034	2.048	2.025			
T_e (°C)	46.41	46.44	47.43			
T_{oc} (°C)	26.00	25.99	26.27			
T_{ow} (°C)	48.37	48.25	49.37			
dT/dt (°C/min)	-0.0300	-0.0254	-0.0272			
t_e (min)	27.5	27	27.5			
H_c (kJ/°C)	0.4546	0.4550	0.4608	0.4568	0.0034	0.75

where:

m_w = mass of water (kg),

T_e = temperature of water when it reaches equilibrium with the calorimeter (°C),

T_{oc} = initial temperature of the calorimeter (°C),

T_{ow} = initial temperature of the water (°C),

dT/dt = rate of temperature change (from graph of time and temperature) (°C/min),

t_e = time when water reaches equilibrium with the calorimeter (min),

H_c = heat capacity of calorimeter (kJ/°C), and

c_{pw} = specific heat of water (4.182kJ/°C).

Table F5. Specific heat values for chickpea by assembled calorimeter method.

Moisture content (%)	Specific heat (kJ/kg°C)					CV (%)	c_p model (kJ/ kg°C)
	Trial # 1	Trial # 2	Trial # 3	Mean	SD		
9.86	1.3772	1.3897	1.3578	1.3749	0.01	1.17	1.5785
13.2	1.5684	1.5812	1.5954	1.5817	0.01	0.85	1.6348
18.17	1.8434	1.8601	1.8452	1.8496	0.00	0.49	1.7185
25.1	1.9823	1.9408	1.9758	1.9663	0.02	1.14	1.8353
35.89	2.1690	2.0774	2.1587	2.1350	0.05	2.35	2.0171
55.97	2.2333	2.2492	2.3089	2.2638	0.03	1.76	2.3555
65.24	2.4645	2.4936	2.4824	2.4802	0.01	0.59	2.5117

Table F6. Specific heat values of chickpea by DSC.

Moisture content (% w.b.)	Temperature (°C)	Specific heat (kJ/kg°C)	c_p model (kJ/ kg°C)
9.86	30	1.154	1.377
9.86	40	1.207	1.426
9.86	50	1.264	1.475
9.86	60	1.312	1.524
9.86	70	1.350	1.573
9.86	80	1.384	1.622
18.17	30	1.713	1.521
18.17	40	1.760	1.570
18.17	50	1.807	1.619
18.17	60	1.849	1.668
18.17	70	1.895	1.717
18.17	80	1.938	1.766
26.54	30	1.748	1.665
26.54	40	1.807	1.714
26.54	50	1.869	1.763
26.54	60	1.927	1.812
26.54	70	1.988	1.861
26.54	80	2.036	1.910
37.89	30	1.866	1.860
37.89	40	1.913	1.909
37.89	50	1.962	1.959
37.89	60	2.016	2.008
37.89	70	2.070	2.057
37.89	80	2.123	2.106
55.97	30	2.078	2.172
55.97	40	2.131	2.221
55.97	50	2.185	2.270
55.97	60	2.236	2.319
55.97	70	2.284	2.368
55.97	80	2.333	2.417
65.24	30	2.358	2.332
65.24	40	2.398	2.381
65.24	50	2.439	2.430
65.24	60	2.485	2.479
65.24	70	2.525	2.528
65.24	80	2.568	2.577

Table F7. Thermal diffusivity values of kabuli chickpea.

Moisture content (% w.b.)	Thermal diffusivity ($\times 10^{-7} m^2/s$)	Mean ($\times 10^{-7} m^2/s$)	SD ($\times 10^{-7} m^2/s$)	CV (%)
9.86	0.9201			
9.86	0.9118			
9.86	0.9332	0.9217	0.0108	1.17
18.17	1.0149			
18.17	1.0366			
18.17	1.0182	1.0233	0.0117	1.14
26.54	1.4936			
26.54	1.5595			
26.54	1.5008	1.5180	0.0362	2.38
37.89	2.2412			
37.89	2.2254			
37.89	2.1679	2.2115	0.0386	1.75
55.97	2.3350			
55.97	2.3054			
55.97	2.3167	2.3191	0.0149	0.64
65.24	2.5350			
65.24	2.5054			
65.24	2.5167	2.5191	0.1490	0.59

Table F8. Determination of solids loss during soaking of chickpea.

Temperature (°C)	Trial #	Solids loss (%)	Mean (%)	SD (%)	CV (%)
100	1	6.31			
100	2	6.20			
100	3	6.22	6.24	0.05	0.94
80	1	5.29			
80	2	5.46			
80	3	5.09	5.28	0.18	3.51
60	1	4.05			
60	2	3.80			
60	3	4.03	3.96	0.13	3.51
40	1	2.63			
40	2	2.71			
40	3	2.50	2.61	0.10	4.06
25	1	1.99			
25	2	1.98			
25	3	1.87	1.95	0.06	3.42